Sustainability of the rock lobster resource in south-eastern Australia in a changing environment: implications for assessment and management

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**SARDI Aquatic Sciences
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Non-technical summary

2009/047 Sustainability of the rock lobster resource in south-eastern Australia in a changing environment: implications for assessment and management

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Outcomes achieved to date

This project has improved assessment of the sustainability of the southern rock lobster resource throughout south-eastern Australia. Investigating whether declining catch rates reflect an actual decline in biomass or are a result of changing catchability or recruitment has improved our understanding of the environmental and catchability impacts on the rock lobster stocks. Consequently, this will improve application of the SRL- assessment model and improve our confidence in the modelling predictions that underpin sustainable management.

Victorian trends in CPUE were not biased by data screening and data selection criteria in preparation for standardisation of CPUE, which provides a more reliable indicator of relative abundance than nominal CPUE (as reported by fishers). Setting TACCs in Victoria involved application of the SRL-fishery stock-assessment model using nominal CPUE up to and including 2011, but this was changed to use standardised CPUE for the 2012 and 2013 assessments. Although CPUE standardisation adjusts for the effects of fishing-year, fishing-month, longitudinal-range, depth-range, and vessel-fisher, it is not feasible, nor appropriate, at this time to incorporate environmental variables into CPUE standardisation for two reasons. One reason is that for the environmental variables tested, the daily fluctuations in CPUE when averaged over month or year have small or negligible effect on the pooled CPUE. The other reason is the lack of ongoing data on key environmental variables such as bottom temperature and dissolved oxygen at spatial and temporal resolutions compatible with the CPUE data. Hence, in the foreseeable future, any detected or hypothesised effect of environmental variables on CPUE or SRL abundance will need to be handled through the SRL-assessment model rather than through CPUE-standardisation models.

The present project confirms spatial trends in puerulus settlement indices are similar in most parts of south-eastern Australia suggesting large-scale oceanographic processes are driving settlement. Puerulus monitoring is a relatively robust indicator of future fishery performance in terms of stock size and CPUE, and should therefore be regarded as important data for providing management advice for SRL resources in south-eastern Australia.

Examination of seasonal stock depletion in Victoria provides a basis for linking catchability values across selected months in the SRL-assessment model, which can now estimate monthly values separately or grouped. Intra-annual cycles of depletion and recovery indicate growth and recruitment are protracted where females precede males by two months. Inter-annual differences in catchability allow correction of CPUE for changing fishing efficiency.

Growth-transition matrices for each sex separately, updated and used in the SRL-assessment model for annual setting of TACCs in Victoria, are now available for the late 1970s, late 1990s and 2000s in each of the main regions and indicate large differences in growth rates between particular sites, but only subtle differences over time. Bimonthly growth-transition matrices are applied monthly for each of six months to account for the SRL moult-growth-recruitment during the second half of the fishing year (November–September) in Victoria.

Management strategy evaluation demonstrates the importance of periodically updating growth transition matrices from on-going tagging programs and the sensitivity to trends in recruitment and catchability for success in accurately determining the TACCs required to meet prescribed fishery management goals. Trends in recruitment and pre-recruitment are robustly monitored, but determining trends in catchability remains problematic.

Objectives

1. Undertake initial evaluation of catch and effort data for a selection of vessels (or skippers) for CPUE standardisation and undertake spatial analysis of rock lobster to depict annual CPUE trends within discrete regions standardised for effects of vessel (or skipper), season, and spatial cell defined by grid-cell and depth range across Victoria.
2. Extend CPUE analyses to test and standardise for, where feasible, the effects of oceanographic variables such as bottom temperature, dissolved oxygen, currents, and wave strength using available data from the Bonney Coast and then test the applicability of these results to western Victoria and determine additional data requirements for extending the analyses to south-eastern Australia.
3. Apply various analyses such as within-season depletion models and the SRL-fishery stock-assessment model applied in the Western Zone of Victoria using available catch and effort data, other monitoring data, and tag release-recapture data to explore variation in annual estimates of catchability and recruitment through time.
4. Investigate evidence for temporal trends in lobster recruitment across the three states, examine evidence of a declining trend since 2003, and examine relationships between yearly environmental signals, and the yearly puerulus index to yearly environmental signals.
5. Undertake growth analyses of available tag release-recapture data to explore variation in annual estimates of growth through time in detail for Victoria and more generally across the three states.
6. Undertake SRL-fishery stock-assessment modelling to explore the sensitivity of biomass projections to altered values of catchability, recruitment, and growth in the Western Zone of Victoria, and, if necessary, make appropriate corrections to components of the SRL-fishery stock-assessment model.
7. Undertake management strategy evaluation, testing stock assessments and exploring implications of alternative assumptions for catchability, recruitment, and growth in the Western Zone in Victoria.

Substantial rise and fall in catch per unit effort (CPUE) of southern rock lobster (*Jasus edwardsii*) (SRL) while under regimes of catch control throughout south-eastern Australia during the late 1990s and 2000s raised questions about the reliability of CPUE as an indicator of relative abundance and the relative importance of the effects of fishing and those of environmental variation on stock abundance. This created a need to distinguish potentially apparent changes from actual changes in relative abundance as indicated by CPUE and to quantify the impacts of daily environmental variation. In addition, there was a need to understand the relative contributing effects of variation in growth, recruitment, catchability, and natural mortality on stock abundance throughout south-eastern Australia.

The project involved initial evaluation of catch and effort data for selection of vessels and fishers for CPUE standardisation in the Victorian fishery and analysis of the effects of environmental variables on daily CPUE in the Southern Zone of South Australia and Western Zone of Victoria. Inter-annual and intra-annual variation in estimates of catchability and recruitment within the Western Zone of Victoria was examined by applying simple stock-depletion models using available within-fishing-year CPUE, catch in numbers and sex composition of the catch monitoring data. Evidence for temporal trends in SRL recruitment across the Victorian, South Australian and Tasmanian rock lobster fisheries was evaluated by examining the pre-recruitment projections, from the SRL-fishery stock-assessment model, and the relationships between yearly environmental signals and the yearly puerulus index. Spatial and temporal variation in growth was explored from available tag release-recapture data in great detail in Victoria and more broadly across all three state fisheries. Stock assessment modelling and management strategy evaluation were undertaken to explore the sensitivity of biomass estimates to catchability, recruitment and growth, and, where appropriate, modify the SRL-assessment model. The sensitivity analyses were undertaken for the Western Zone of Victoria, but enhancements to the SRL-assessment model and upgraded manual and model specifications benefit all three states.

The CPUE standardisation adjusted for the effects of vessel-fisher, region (six regions with three in each zone comprising areas defined by 10-minute intervals of longitude), fishing depth-class (<40 m, and ≥40 m), fishing month, and fishing year (November–October). Two methods of generalised linear modelling, referred to here as the Delta-X Method (combines gamma and binomial probability distribution functions) and the Tweedie method (Tweedie probability distribution function only), were applied for CPUE standardisation of Victorian data. Statistically, the Tweedie method more elegantly incorporates zero CPUE values, but is computationally slow, whereas the Delta-X method implemented using the statistical package SAS is computationally fast and easier to use. Appropriate CPUE data screening, selection and standardisation procedures showed that trends in CPUE for (a) 'unscreened' data (as reported), (b) 'screened' only data, and (c) 'screened and selected' data were very similar to each other, indicating that screening and selection of the data did not alter the CPUE trends. However, all of these three trends were very different from the trend in CPUE for (d) 'screened, selected and standardised' data. Standardised CPUE trends exhibited markedly greater stock depletion than non-standardised CPUE trends for Victoria as a whole, for each of the Western Zone and the Eastern Zone, and for each of the six regions.

Exploring the influence of environmental variables on daily CPUE in the Southern Zone using generalised linear modelling indicated that wind speed, wind direction, wind stress and sea surface height had no statistically meaningful impact on daily CPUE. With increasing wave height, CPUEs were lower on the same day, but higher 3 or 4 days after high swells. CPUEs were also higher during the 3−4-day period prior to the 7-day full moon period, but decreased during the period after the full moon. As bottom temperature increased, CPUE declined. Looking at the data time series, CPUEs were not affected by one of the strongest upwelling events on record (February of 2008). Overall, environmental variables explained only an additional 7% of daily variation in log-transformed CPUE with 84% explained by year and month adopted for monitoring longer-term changes in SRL abundance.

It is not feasible, nor appropriate, at this time to incorporate environmental variables into CPUE standardisation for South Australia's Southern Zone, or for any other management zone in south-eastern Australia, for two reasons. One reason is that for the environmental variables tested, the daily fluctuations in CPUE when averaged over month or year have small or negligible effect on the pooled CPUE relative to change in abundance and non-environmental effects (such as location, depth and possibly seasonal catchability). The other reason is the lack of data on key environmental variables such as bottom temperature and dissolved oxygen at an appropriate spatial and temporal resolution. Hence, any detected or hypothesised effect of environmental variables on CPUE or SRL abundance will need to be accounted for through the SRL-assessment model rather than through CPUE standardisation models.

Patterns in Victoria's Western Zone of declining monthly standardised CPUE expressed as SRL number per potlift through each fishing year are indicative of depletions for males and females combined during February–May, for females during November–May, and for males during January–June, but then rising during June–October for females and July–December for males. These trends are consistent with the hypothesis that females are fully recruited when the fishing year opens in November after the 5-month closure, whereas males undergo protracted recruitment during July–December and are not fully recruited until January. For application of the SRL-assessment model, these patterns provide a basis for varying catchability seasonally and for protracted recruitment (through growth transition matrices) over several months. Potential behavioural responses to seasonal conditions and to biorhythms such as the reproductive cycle create uncertainty about how best to vary catchability and recruitment seasonally. Application of depletion models for the depleting months of the intra-annual cycles of depletion and recovery from protracted growth and recruitment indicate females precede males by two months and that catchability for females and males are very similar. Estimation of inter-annual differences in catchability allows correction of time series of standardised CPUE for trends in changing fishing efficiency.

Spatial trends in puerulus settlement indices (PSI) are similar in most parts of south-eastern Australia suggesting that large-scale oceanographic processes drive settlement, particularly in South Australia and Victoria. The ability to predict future fishery recruitment based on annual PSIs is an advantage for the fishery. In particular, the use of PSI to forecast future levels of modelled recruitment as an indicator of likely, or at least plausible, future changes in stock size and thus catch rates has clear advantages. Puerulus numbers are a relatively robust indicator of future fishery performance and should therefore be regarded as an important data source for providing advice on management of SRL resources within south-eastern Australia.

Variation in spatial and temporal length-increment data for SRL off Victoria is remarkably high and growth is highly plastic depending on habitats and prevailing environmental conditions. In general, mean annual length-increment of SRLs larger than 100 mm carapace length increased from the late-1970s, through late-1990s, to 2000s, and approximately from west to east. During the 2000s, differences in mean annual length-increment for selected sizes were higher among 13 separate sites than among 6 separate fishing years at one of these sites.

Growth of SRL varies among regions, so separate growth-transition matrices are required for different regions in the SRL-assessment model. For Victoria, it is important to have separate matrices for each sex in the Portland, Warrnambool, Apollo Bay and Queenscliff Regions. These growth-transition matrices have been determined for the late 1970s, late 1990s and 2000s and for each year between the late-1970s and late-1990s and between the late-1990s and 2000s, where the annual matrices determined by interpolation vary inter-annually smoothly from one period to the next. This allows taking advantage of the flexibility of the SRL-assessment model, which has facility to vary growth-transition matrices spatially and temporally.

Management strategy evaluation indicated that changes over time in natural mortality and growth do not markedly affect the performance of the management procedure for Victoria, which is dependent on the application of models

for future projections, particularly given growth parameters can be periodically updated by ongoing tagging programs. In contrast, trends in catchability and recruitment can lead to management goals not being satisfied, with trends in catchability the most problematic because such trends lead to bias in stock assessment outcomes even if data sources which provide unbiased information on abundance are available for assessment purposes. The implication for stock assessments of SRL is that catchability should not be considered a constant over long periods of time. Rather, it should be either re-estimated for discrete time periods or temporal change accounted for with a temporal model of catchability.

Keywords: CPUE standardisation, CPUE environmental correlation, recruitment, growth, catchability, MSE.

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Background

The present report has all the prescribed sections of a standard FRDC report and each of the sections Background, Need, Objectives, Methods, Results and Discussion has sub-sections related to each of six reports and a literature review, which address the project objectives. Information in the appendices include information on intellectual property (Appendix 1), staff undertaking the project (Appendix 2), and a list of outputs from the project (relevant scientific papers and presentations) (Appendix 3). The report is designed to provide an account of the work from the project, but the six reports and literature review are each designed to stand alone as a technical report or manuscript in preparation for submission to an internationally reviewed journal (Appendices I−VII).

Southern rock lobster (*Jasus edwardsii*) (SRL) CPUE and biomass in Victoria, South Australia and Tasmania rose since the mid-1990s, but then trended downwards. Stock assessment of SRL in these jurisdictions is dependent on catch per unit effort (CPUE) as an index of relative abundance that can be expressed as number or mass of SRL per pot-lift. In Victoria, despite reduced catches following implementation of catch-quota management in the Western Zone, CPUE continued to decline during the 7-year period from 2003–04 fishing year (16 November–14 September) to 2009–10 (Feenstra 2013). Catch has been comparatively constant in the Southern Zone of South Australia, but CPUE and median biomass projections have declined over the same period. This occurred while puerulus settlement on collectors increased during 2003–06 (Linnane, McGarvey *et al.* 2011), suggesting the recent changes affecting CPUE are among the post-puerulus settlement life stages rather than among the earlier planktonic life history stages. In Tasmania, similar declines occurred state-wide 2–3 years after those in Western Victoria and South Australia (Gardner, Hartmann *et al.* 2011; Phillips, Melville-Smith *et al.* 2010).

For fisheries in general, catches resulting from fishing operations of commercial fishing vessels depend largely on three factors. These factors are (a) vessel characteristics such as skill of operators, fishing gear and technological equipment; (b) characteristics of the fished population such as abundance level, spatial distribution and availability to the fishing gear; and (c) environmental and physiographic conditions such as weather, hydrology, depth and substrate. It is necessary to identify and, if possible, separate the effects of these factors to interpret CPUE correctly. Hence, CPUE should be 'standardised' to account for factors such as differences in fishing power among vessels (or differences in skill of skippers) and variations in seasonal and spatial patterns of fishing from year to year when using a time-series of CPUE to provide an inter-annual trend representative of relative abundance. This type of analysis adjusts for potential effects of changed fleet dynamics; e.g. grounds fished in a particular year might be altered by poor weather conditions.

Environmental factors can also bias CPUE to produce 'apparent change' in relative abundance (e.g. low water temperature may reduce feeding activity), or to produce 'actual change' in relative abundance (e.g. high temperature may increase natural mortality). If this were the case, then ideally, temperature below a critical value will be incorporated as a continuous variable in CPUE standardisation, and temperature above the critical value might be treated as a variable in the SRL-fishery stock-assessment model driving natural mortality. Inaccurate catch or effort in logbook returns also biases CPUE as an indicator of relative abundance; hence, where feasible CPUE needs to be adjusted for misreporting with appropriate correction factors. Where this is not feasible, it is appropriate to undertake sensitivity analyses.

CPUE can also be a biased indicator of relative abundance when there is hyper-depletion caused by apparent rapid fish-down from targeting aggregations containing a small proportion of the overall population or where there is hyper-stability caused by apparent stability from serially-depleting aggregations containing a major proportion of the harvestable component of the population. Where hyper-depletion or hyper-stability occurs, 'catchability' is not constant for all population sizes and needs to be treated as variable in the assessment model.

Hence, the project was designed to address several uncertainties in the fishery:

- to distinguish potentially apparent changes in relative abundance from actual changes in relative abundance as indicated by CPUE;
- to quantify the impacts of daily environmental variation on CPUE;
- to investigate evidence for temporal trends in SRL recruitment across the three states;
- to determine the stock assessment and management implications of increased uncertainty in a changing environment; and

- to make recommendations on future research and development directions, appropriate monitoring strategies, assessment methods, and robust management strategies to address the increased uncertainty.

Addressing CPUE as an indicator of relative abundance requires identifying the components of CPUE values that represent:

- apparent bias in relative abundance, but can be adjusted by standardisation (e.g. vessel, fisher, temporal and spatial effects) or by correction factors (e.g. misreporting);
- apparent bias in relative abundance, but can be accommodated by adjustment in the SRL-assessment model (such as by allowing for time-varying catchability with predicted population size, specific environmental conditions, or SRL biorhythms associated with ovarian maturation and moult cycle); and
- actual change in abundance, caused by change in recruitment or mortality.

During winter, the westward coastal current brings relatively warm water from the Great Australian Bight (and Leeuwin Current) to the regions of the Southern Zone of eastern South Australia, Western Zone of Victoria, and north-western Tasmania. When the coastal current increases, stronger shelf flows to the south-east change the distribution of phyllosoma larvae of SRLs, and these warm surface-nutrient-poor waters lead to reduced productivity. During summer, the coastal current reverses and episodic upwelling of cold-nutrient-rich waters occurs across the Bonney Coast and Otway shelves (Levings and Gill 2010) with increases in primary productivity and flow-on effects up the food chain. Off the west coast of Tasmania, the upwelling is less pronounced and the ocean circulation is influenced by the coastal trapped wave scattering by Bass Strait (Evans and Middleton 1998). The complexity of the interactions of these systems leads to high uncertainty in terms of how the environmental drivers might be affecting CPUE or abundance of SRLs now and into the future. Environmental drivers that potentially affect the SRLs are temperature, dissolved oxygen, bottom currents, and turbidity that can lead to re-suspension of bottom sediments and detritus. In addition, survival of phyllosoma larvae and certain components of the pelagic food chains in surface waters are likely to be sensitive to changes in ultraviolet solar radiation.

Three alternative biological hypotheses associated with the stocks of SRLs are posed here as a basis for exploring links between CPUE (or relative abundance) and potential environmental drivers.

1. No change in abundance, but reduced catchability because of changed ambient environmental conditions.

   Reduced catchability might be caused by reduced activity, notably from lower temperatures, or reduced need to feed from changed conditions, or alternatively higher availability of food from changed conditions might have reduced the need for SRLs to enter pots. Changed environmental conditions can lead to changes in the inter-moult period, which, in turn, can markedly affect seasonal patterns of catchability. Furthermore, changed conditions can lead to changes in sea-lice activity, which can affect catchability through changes in bait durability.

2. Reduced abundance from reduced recruitment to harvestable size caused by increased pre-recruit natural mortality from changed ambient environmental conditions.

   Reduced recruitment through increased pre-recruit natural mortality might be caused by unfavourable ambient conditions (including temperature), increased predation, reduced food availability, or loss of suitable habitat for puerulus settlement.

3. Reduced abundance of SRLs of harvestable size caused by decreased growth rates from changed ambient environmental conditions reducing number and rate of pre-recruits reaching the legal minimum length.

   Decreased growth rates might be caused by ambient conditions reducing moult-increment, or increasing the inter-moult period, or by reduced food availability.

A first-step simplifying approach to distinguishing between these hypotheses is to investigate the inter-annual effects evident in CPUE for each of catchability, recruitment, and growth rates separately. It is feasible to address potential changes in parameters adopted for catchability, recruitment, and growth from available monitoring and tag release-recapture data, with a combination of simple models and the main synthetic models developed for fishery stock assessment and management strategy evaluation.

The above three hypotheses depend on the assumption that CPUE, and possibly abundance, declined because of environmental effects on the biology or behaviour of SRLs. As an alternative to these biological hypotheses, a fourth hypothesis—a socio-economic hypothesis—is considered to cover the possibility of a non-biological cause to the decline in reported CPUE.

4. Apparent reduced CPUE caused by changes in fleet dynamics and in rates of reporting or high grading from changed economic conditions during recent years.

   Changes in fleet dynamics, reporting and high-grading would affect CPUE. These changes would be driven by changes in markets, the management environment and costs. For example, change in price of fuel or market price for different colour grades would affect the spatial location of effort.

This project was not designed specifically to address the effects of climate change on the SRL stocks, but it was expected to contribute to identifying key environmental variables that affect the stocks. The project was designed to relate the abundance of SRLs at various post-puerulus settlement life-history stages, as indicated by CPUE, to environmental variables such as temperature, dissolved oxygen, bottom currents and turbidity using existing data. Understanding how these environmental drivers are likely to vary in response to climate change requires broad-scale investigation and establishing widespread and ongoing oceanographic monitoring systems throughout south-eastern Australia. The Australian Government has invested in infrastructure for oceanographic monitoring through the Integrated Marine Oceanographic System (IMOS); however, there is a need to identify the key environmental variables for monitoring and to determine the appropriate spatial and temporal resolution for that environmental monitoring required for forecasting the long-term effects of climate change on harvested species. The present project largely met these goals for SRL and indicates that it is necessary to obtain additional types of data, and data at a much higher resolution to improve the links between the stocks and environment and to provide the basis for forecasting future stocks from predicted environmental conditions or alternative environmental scenarios.

Need

Recent declines in catch, CPUE and model-estimated stock biomass of SRL throughout south-eastern Australia were surprising at a time when the fishery was managed by Total Allowable Commercial Catches determined by stock assessment modelling. The SRL-fishery stock-assessment model applied in Victoria, South Australia and Tasmania, which is dependent on CPUE as an index of relative abundance expressed as number or mass of SRLs per pot-lift, indicated that the observed declining CPUE trend was caused by below-average recruitment. There was concern that CPUE may also be driven by changes in catchability influenced, for example, by environmental effects, fleet dynamics, fisher behaviour, or SRL behaviour. Hence, there was a pressing need to determine whether the observed falling CPUE represented an apparent decline in relative abundance caused by reduced catchability or an actual decline caused by reduced recruitment, reduced growth, or increased natural mortality, or a combination of these fishery and biological processes. Addressing this need requires answering two important questions. What are the implications of varying catchability, recruitment, growth or natural mortality for future assessments? What monitoring and management strategies are most robust in the face of these uncertainties?

Objectives

1. Undertake initial evaluation of catch and effort data for a selection of vessels (or skippers) for CPUE standardisation and undertake spatial analysis of rock lobster to depict annual CPUE trends within discrete regions standardised for effects of vessel (or skipper), season, and spatial cell defined by grid-cell and depth range across Victoria.
2. Extend CPUE analyses to test and standardise for, where feasible, the effects of oceanographic variables such as bottom temperature, dissolved oxygen, currents, and wave strength using available data from the Bonney Coast and then test the applicability of these results to western Victoria and determine additional data requirements for extending the analyses to south-eastern Australia.
3. Apply various analyses such as within-season depletion models and the SRL-fishery stock-assessment model applied in the Western Zone of Victoria using available catch and effort data, other monitoring data, and tag release-recapture data to explore variation in annual estimates of catchability and recruitment through time.
4. Investigate evidence for temporal trends in lobster recruitment across the three states, examine evidence of a declining trend since 2003, and examine relationships between yearly environmental signals, and the yearly puerulus index to yearly environmental signals.
5. Undertake growth analyses of available tag release-recapture data to explore variation in annual estimates of growth through time in detail for Victoria and more generally across the three states.

6. Undertake SRL-fishery stock-assessment modelling to explore the sensitivity of biomass projections to altered values of catchability, recruitment, and growth in the Western Zone of Victoria, and, if necessary, make appropriate corrections to components of the SRL-fishery stock-assessment model.
7. Undertake management strategy evaluation, testing stock assessments and exploring implications of alternative assumptions for catchability, recruitment, and growth in the Western Zone in Victoria.

Methods

CPUE screening, selection and standardisation

Values of CPUE calculated from catch and fishing effort data submitted on routine mandatory logbook returns by fishing licence holders are used as an indicator of relative abundance for stock assessment of southern rock lobster (*Jasus edwardsii*) and giant crab (*Pseudocarcinus gigas*). This approach occurs in Victoria, South Australia, and Tasmania, but for the purpose of the present study, the Victorian data were processed to produce time series of standardised CPUE for application in the SRL-fishery stock-assessment model.

Victorian stock assessments up to and including 2011 depended on 'nominal' CPUE as the index of abundance for each year (or for part of the year) by dividing total catch by total fishing effort. As in many fisheries, several features of lobster pot fishing complicate the interpretation of CPUE and potentially bias CPUE as an indicator of relative abundance over short and long periods. These features include targeting between southern rock lobster (SRL) and giant crab, and differences in fishing practice required between the two species, and differences among fishers in their levels of fishing skill, experience, and aspirations. There are also differences among fishing vessels in capacity to move among fishing sites, to locate fishing sites with navigational aids available, and to operate under varying conditions, as well as differences among fishing vessels in the number of pots carried (licensed) and the capacity to deploy those pots most effectively. Other features include progressive adoption of new technology to increase fishing power of vessels, and fluctuations and trends in market demand for SRL and giant crab, and profitability of the fishery.

Adjustments for some of these effects are through the process known as 'CPUE standardisation' by application of statistical techniques involving generalised linear models. Statistical complications arise with the 'structure' of the data, particularly in relation to the presence of zero CPUE values; hence, before applying these models, the data require testing for the most appropriate 'probability density function'. Often zero CPUE values are ignored, adjusted by the addition of a small constant, or CPUE values are derived by aggregating catch over larger units of fishing effort. In the present study, however, these approaches were avoided because they can bias standardised CPUE trends, and they preclude examination of the data at the resolution they were collected. Although only less than 1 per cent of the records used in the present study are zero CPUE values, the approach explored two methods of including zero CPUE values in statistical modelling (Appendix 1).

In Victoria, SRL catch and effort data are managed and processed routinely through a series of electronic systems. These systems are designed to facilitate data entry, secure archive, verification, validation, summary and analysis. For determining total catch, nominal (as reported) fishing effort, nominal CPUE, and mean mass of SRL, the systems use all the available data. For determining 'standardised CPUE' as an input to stock assessment, the data were processed through an additional system referred to as 'CPUE data screening, selection and standardisation'. Data screening involved excluding erroneous or incomplete data. Standardisation of CPUE over the 33-year period of fishing years (November–October) from 1978–79 to 2010–11 was undertaken using data from 'vessel-fishers' (from a fisher specific to a vessel). In each of the Western Zone and Eastern Zone separately, to be selected, a 'vessel-fisher' must have contributed data in more than any two fishing years with a minimum of 200 records, where each record was for more than 15 lobster pots lifted on a particular day targeting SRLs. Statistical modelling of CPUE standardised for the main effects of fishing year, fishing month, region, depth-category, and 'vessel-fisher' and for their interactions (excluding those with vessel-fisher).

CPUE environment correlation

CPUE is widely used to determine annual total allowable commercial catches (TACCs) as part of SRL harvest strategies. One of the basic assumptions underpinning this process is that changes in CPUE reflect changes in relative abundance. However, it is widely accepted that factors other than abundance may affect CPUE and these are often assumed to act as a time-varying multiplicative factor known as catchability. In South Australia, CPUE within the Southern Zone of the fishery decreased by about 70% from 2002 to 2009. Whereas there are clear indications that recruitment to the fishery declined dramatically during this period, there was a need to investigate what impact, if any, environmental factors may also have had on CPUE. The present study examined the daily effect on CPUE of five environmental variables: bottom temperature, waves, moon phase, wind, and sea surface height. A generalised linear model analysis was used to identify variables that had a statistically identifiable influence on daily CPUE (Appendix II). The analyses were repeated in the Victorian Western Zone to test the wider applicability of the method.

Logbook-derived CPUE are reported in the 8 months from October to May in the South Australian Southern Zone and environmental data were obtained from several sources. Sea surface height data and wind data (speed, direction and stress) were available from Portland, Victoria. Wave data (height and period) were supplied from the United States National Oceanic and Atmospheric Administration wind-wave oceanic model, using values from an 80 m depth location off Cape Jaffa. Bottom temperature data were collected from 60 m depth off Southend, but were only available for specific time periods during 1998−2002 and 2006−2008, which limited the daily time frame of the analysis. A total of 1258 daily data points were utilised. For the Victorian Western Zone, two CPUE data sets were used separately ('non-screened and non-selected data' (as reported by licence holders) and 'screened and selected data').

A generalised linear model was used to quantify the relationship between log-transformed CPUE and the environmental variables available for the Southern Zone. The main initial model was as follows:

$$\begin{aligned} ln(Catch\ rate) = {} & Year + Month + Year{:}Month + WaveHeight + WavePeriod + Temperature + \\ & Moonphase + AlongshoreWind + TotalWind + Depth + SSH + MFAindex + \\ & \varepsilon_{Normal} \end{aligned}$$

This model also included bivariate interactions between season or month and the environment variables, as well as moving average lag (over 1 to 5 days) terms for wave height, bottom temperature, and alongshore wind stress. A non-linear weighting of the daily data points was used to give greater statistical influence to days with more fishing (as more potlifts). A backward selection procedure was used, where the full model was simplified step by step, and terms which such as those representing locality did not contribute sufficiently (using small sample corrected AIC and adjusted R^2) to model improvement were removed. Zero catch rates that were an issue for CPUE standardisation were not an issue because catch rates used at the resolution of daily catch rates for the entire fleet across the zone did not have zero values. Full details are provided in Appendix II.

Seasonal depletion

Changing from annual to monthly time steps as part of applying a recently upgraded version of the SRL-assessment model in each of the Western Zone and Eastern Zone of the Victorian Rock Lobster Fishery created a need to consider patterns of stock depletion evident during each fishing year from November to the end of October. Patterns of depletion through the fishing-year were examined for each of males and females of size above legal minimum length. These patterns were then considered against the hypothesis that SRLs moult and grow to produce a recruitment-pulse adding to the residual stock either prior to or shortly after the start of the fishing year before subsequent progressive stock depletion through the remainder of the fishing-year. The difficulty of the approach is to select a series of months that are not affected by recruitment or behavioural changes associated with reproductive biorhythms (Appendix III).

Exploration of within-fishing-year stock depletion from November to October used mandatory catch and effort logbook returns as monthly 'Tweedie standardised' CPUE expressed as number of SRLs per potlift (Appendix I). These CPUE trends were considered for (a) females and males combined for each of the 34 fishing-years from 1978–79 to 2011–12 in each Victorian zone, and (b) males and females separately (derived from sex ratio data collected at-sea by scientific observers) for each of the seven fishing-years from 2005–06 to 2011–12 in the Western Zone.

Long-term trends in the within-fishing-year depletion pattern for females and males combined were examined by plotting five sets of monthly CPUE averaged over 3−6 consecutive fishing years from the 34-fishing-year time-series from 1978–79 to 2011–12. The five sets of consecutive fishing years were selected on the basis that the pattern of their monthly CPUE values was similar from year to year. For females and males separately, annual estimates of catchability for the fishing years from 2005–06 to 2011–12 and population size at the beginning of November for females and beginning of January for males were estimated from the monthly standardised CPUE data and monthly catch in numbers using a simple depletion model. This provided annual estimates of catchability for the two sexes combined or separately and number of SRLs in the recruited population (i.e. SRLs larger than the legal minimum lengths) at the start or at some instant during the fishing year. The within-year depletion model is suitable for SRLs where there is a pulse of recruitment following moult increment, after which time the stock is progressively depleted until the next pulse of recruitment. Inter-annual trends in catchability provide a basis for adjusting standardised CPUE used for stock assessment as an index of relative abundance for the effects of changing fishing efficiency (Wright, Caputi *et al.* 2006).

Recruitment variation

Puerulus monitoring has been undertaken across south-eastern Australia since the early 1970s, but quantified estimates of settlement did not develop until the 1990s. Initially, research was driven by the twin aims of understanding long-term settlement trends (Appendix IVa) and early life history biology. More recently, the focus changed to examining the use of annual puerulus settlement indices (PSI) as indicators of future recruitment to the fishable biomass (Appendix IVb). This largely stems from the success of this relationship in Western Australia where future commercial catches of *Panulirus cygnus* can be successfully predicted from settlement indices using a 3–4-year time lag (Caputi, Brown *et al.* 1995). Similar relationships have also emerged in specific regions of some *J. edwardsii* fisheries (Booth and McKenzie 2009; Gardner, Frusher *et al.* 2001). The aims of the present study were to examine firstly the spatial trends in puerulus settlement across South Australia, Victoria and Tasmania, and secondly the relationship between the annual settlement index and subsequent model-estimated recruitment into the fishery within each region with a range of time lags.

Details of the statistical analyses undertaken for this study are provided in Appendix IVb. In South Australia, data were analysed from five puerulus monitoring sites in the Southern Zone (Blackfellows Caves, Livingstones Bay, Beachport, Cape Jaffa and Kingston) and from four sites in the Northern Zone (Stenhouse Bay, Marion Bay, Maclaren Point and Taylor Island) (Appendix IVb, Figure 1). Data for Victoria were also analysed from two sites in the Western Zone (Port Campbell and Apollo Bay) and for Tasmania from four sites (Recherche Bay, South Arm, Bicheno and Flinders Island).

The relationship between puerulus settlement indices (PSIs) and recruitment was investigated from sampling periods between 1991 and 2010 under a range of time lags from 1 to 5 years. Estimates of recruitment to the fishery were derived from the length-based population dynamics model used for annual stock assessment of the SRL fisheries in South Australia, Victoria and Tasmania.

In South Australia, PSI estimates from the Northern Zone and Southern Zones were compared with zone-wide recruitment estimates from these regions. As puerulus sampling is not undertaken in the Eastern Zone of Victoria, recruitment estimates from this region were correlated with annual settlement from the Western Zone. In the Eastern Zone, the recruitment estimates are representative of the western regions, where most of the catch and data are from, and provide no information in the eastern regions, particularly east of Wilsons Promontory. Within Tasmania, PSIs were correlated with recruitment estimates from the two north-eastern management sub-regions where puerulus sampling was undertaken (Appendix IVb, Figure 1) and which showed the highest self-consistency in annual puerulus numbers observed.

Growth variation

Statutory obligations require annual stock assessment to set a TACC for each of Victoria's Western Zone and Eastern Zone. These TACCs are estimated using the SRL-assessment model designed for assessment of the SRL fisheries in Victoria, South Australia, and Tasmania and developed over the past 15 years. This size-structured population dynamics model, for each sex separately, represents growth with a matrix specifying the probability of a SRL growing from one size-class to each of a range of other possible size-classes in a specific time step. Until recently, the model was applied each year in Victoria to each zone in annual time-steps applying a single growth-transition matrix. For the 2012 stock assessment, the latest version of the model was operated with 5-mm size-classes (starting size 60 mm carapace length) with updated growth-transition matrices from the present study, with a need to consider spatial and temporal variation in growth as part of future stock assessments (Appendix V).

Earlier studies of growth of SRL in southern Australia and New Zealand found spatial and temporal differences in patterns of length-increment. The present study explores spatial and temporal variation in length-increment in Victoria from tag release-recapture length-increment data available from all sources for the 36-year period from 1975–76 to 2010–11 fishing years.

Tag release-recapture data for SRLs pooled variously into samples at different spatial and temporal resolutions were analysed with stochastic models expressing variation in growth among individuals in a population through the random von Bertalanffy–Fabens parameter k alternatively represented by the three positively distributed probability density functions: gamma, Weibull and log-normal. The most appropriate probability distribution for each sample of tag release-recapture data was identified using a statistical test known as 'the approximation to Kullback's information mean'.

The study compared annual length-increment between Victoria's Western Zone (WZ) and Eastern Zone (EZ) for males and females separately with all sources of tag length-increment growth data pooled for the 36-year period from 1975–76 to 2010–11 fishing years. Comparisons were then made among six Victorian regions and among three periods referred to as Late 1970s, Late 1990s and Most 2000s within each of the six regions where there were sufficient data. The study then compared SRL annual length-increment among 13 specific sites (data from a

14th site were pooled with one of the 13 sites) from the annual fixed-site surveys (from 1995–96 to 2010–11 fishing years in EZ and from 2001–02 to 2010–11 fishing years in WZ). Finally, the study compared SRL annual length-increment among six separate fishing years from 2001–02 to 2006–07 for one site from the annual fixed-site survey that had a particularly large sample size.

Management strategy evaluation

Environmentally-driven changes in recruitment and high fishing mortality are likely causes for the decline in the harvestable biomass of SRLs across southern Australia, although changes in natural mortality, catchability and growth may also have had effects. Management strategy evaluation has previously been applied to SRLs off Victoria to evaluate the impact of spatial structure on the performance of the Harvest Control Rule which has subsequently been replaced by the Harvest Control Rule specified in the Victorian Rock Lobster Fisheries Management Plan 2009 (Department of Primary Industries 2009). This management procedure aims to recover the resource to a target level of exploitable biomass and to maintain egg production above a limit reference point. The management procedure is evaluated in terms of (a) catches, (b) risk of not achieving conservation goals, and (c) bias of estimates from the stock assessment given scenarios in which natural mortality, catchability, growth and recruitment are exhibiting future trends. Management strategy evaluation is used to evaluate a management procedure inferred for the Western Zone in Victoria under the ideal situation in which the assumptions made when forecasting abundance are correct and in which key production- and fishery-related parameters (growth, natural mortality, recruitment and catchability) exhibit trends over time (Appendix VIa).

Management strategy evaluation and most other components of the project are dependent on the SRL-fishery stock-assessment model. Management strategy evaluation applies the model directly, whereas the other components involved evaluating data for the model (notably ‘CPUE environment correction’, ‘Seasonal depletion’, and ‘Recruitment variation’) or preparing data for direct input to the model (notably ‘CPUE screening, selection and standardisation’ and ‘Growth variation’). Continued enhancement of the stock assessment model was an integral part of the present project to the extent that the ‘Model specifications’ (Appendix VIb) and ‘User manual’ (Appendix VIc) form part of the report. These two appendices provide details of parameter estimation and hindcasting, and whilst enhancements for model forward projections were markedly progressed as part of the project, the model specifications and user manual for this will be reported as part of a separate project.

Review of environmental effects

A detailed review of the literature titled ‘Environmental effects on lobster and crab fisheries of the world’ is provided in Appendix VII.

Environmental variation shapes species distribution, ecology and, in some decapod crustaceans, their marketability through colour and size differences. Many lobster and crab species have a wide latitudinal distribution and therefore are exposed to significant abiotic gradients throughout their geographic range. Environmental factors affect both lobsters and crabs throughout their complex life cycle, including timing and length of the spawning period, duration and quality of the larval stages, level and spatial distribution of settlement, growth rates and size of juveniles, size-at-maturity, and catchability. Understanding the general trends between environmental variation and crustacean population dynamics can be used to better assess stock sizes and future biomass, including whether changes in CPUE are due to changes in catchability or changes in stock. It may also be used to infer stock responses to future climate change scenarios.

The most consistent environmental response is of growth and reproduction to temperature. Growth rate increases with increasing temperature in a parabolic function, tapering and then declining as the boundaries of thermal tolerance are reached. With increasing temperature the intermoult decreases and moulting occurs earlier. Once the upper thermal boundary is reached, increases in temperature can become lethal, increasing the intermoult and reducing the moult increment. Declines in temperature can suppress moulting, and consequently crustaceans rarely moult in winter. Increasing temperature decreases the time for egg incubation and larval development and reduces maturational age of adults. Within a reproduction season, cold temperatures can lead to delayed or skipped reproduction, and delayed hatching.

Increase in water temperature increases catchability in clawed and spiny lobsters. Catchability generally decreased with an increase in population density due to agonistic interactions around traps; however, in some species catchability increased with increases in population density. Full moon and wind were reported to have mixed effects on catchability, but no consistent effect that could be used to moderate stock assessments.

Settlement in a number of species depends on current strength, increasing with the strength of certain local currents. This pattern may be due to the physical movement of water bodies and their advective effects or the co-varying changes in primary production or temperature. Similarly, when wind has had an effect on catchability or recruitment it is likely to be due to co-varying factors such as temperature. Salinity has no generalised effect on any developmental stage of decapods as there are different physiological responses and behaviour to cope with changes in salinity.

Decapod crustaceans can tolerate a wide variety of conditions and have flexible life histories to respond to conditions throughout their broad geographic ranges. As temperature and ocean pH change with climate change there are a number of potential risks to crustacean stocks. Early or late hatching, as a result of shifting temperature regimes, could result in decapod larvae missing the primary peak of zooplankton blooms. This “match-mismatch” would affect the size and quality of settlement pulses. There is already evidence of longer and later spawning season in larger female *Homarus americanus*, which is hypothesised to be a response to increased concurrence of larvae with plankton blooms. As temperature increases, increased catch rates due to increased activity may be another side-effect of climate change.

Results and Discussion

CPUE screening, selection, and standardisation

A total of 535,556 records from Victorian SRL and giant crab pot fishing commercial catch and effort logbook returns extracted were available from 1978–79 to 2010–11, of which 9.4% were rejected through 10 steps of data screening for exclusion from CPUE standardisation to avoid anomalous data. The screened data included 667 separate fishers and 820 separate vessels engaged in the fishery across Victoria and from this information 1480 ‘vessel-fishers’ could be computed. Screened records from the 1480 vessel-fishers indicate (a) negligible zero CPUE values, (b) a CPUE mode at 0.25–0.49 kg/potlift, (c) wide range of CPUE values with high values for a small proportion of the potlifts (right-skew), and the vessel-fishers take a mean annual catch of <2 t, with a negligible number taking >10 t.

A model selection procedure indicated that a generalised linear model with the gamma probability density function (with log link) (for non-zero CPUE values) paired with the binomial probability density function (with logit link) (for inclusion of zero CPUE values) best fits the available CPUE data. An alternative probability density function in the generalised linear model, which equally well fitted the CPUE data, is the Tweedie probability density function. This can uniformly handle large proportions of zeros in the data and eliminates the need for splitting the data into zero and non-zero parts. Referred to here as the Delta-X Method and the Tweedie Method for CPUE standardisation, the Tweedie Method is statistically the more elegant method because it more easily incorporates zero values, but is computationally slow on computers, whereas the Delta-X Method implemented in the statistical package SAS is computationally fast and easier to apply. There are negligible differences in the trends from the two methods.

Trends in CPUE for (a) ‘unscreened’ data (‘nominal CPUE’ as reported), (b) ‘screened’ only data, and (c) ‘screened and selected’ data were very similar to each other, indicating that screening and selection of the data do not alter the trends. However, all of these trends were very different from that in CPUE for (d) ‘screened, selected and standardised’ data. Standardised CPUE trends from 1978–79 to 2010–11 exhibited markedly greater depletion than non-standardised CPUE trends for Victoria as a whole, for each of the Western Zone and Eastern Zone, and for each of the six regions (Appendix I, Figures 10–11).

Vessel-fisher is expected to be a better unit for standardisation of CPUE than either ‘fisher’ or ‘vessel’ alone, because fishing power of a ‘vessel-fisher’ depends on both the attributes of the fisher (e.g. skill, persistence, targeting practice) and the attributes of the vessel (e.g. size, fishing and handling gear, and navigational aids). Participation by the vessel-fishers in the fishery measured as fishing effort (potlifts, days or years) varied markedly from a single day to 31 years of fishing (followed by 30, 25 and 24 years). Those vessel-fishers of low participation, including undetected errors in identity of fisher or vessel, provide little or no information on inter-annual, monthly or spatial trends, but contribute to variation and noise in the CPUE data. Given the skill level of a fisher increases with experience, there is an argument for excluding any fisher or vessel-fisher from the analyses if the participation is less than a defined number of fishing days or years in the fishery. This has the benefit of reducing the number of vessel-fishers, without markedly reducing the number of records retained for analysis.

CPUE environment correlation

Model pruning via backward selection reduced the variables in the model to linear terms involving wave height, wave period, lagged wave height, bottom temperature and moon phase. Wind speed, wind direction, wind stress and sea surface height had no statistically meaningful impact on daily CPUE.

The strongest effects on CPUE in the South Australian Southern Zone were from wave action, where CPUE declined with increasing wave height on the same day (Appendix II, Tables 2−3). However, 3 or 4 days after high swells (Appendix II, Figure 3), higher CPUEs were observed. CPUEs were also higher in the 3−4-day period prior to the 7-day full moon period, but decreased in the period after the full moon (Appendix II, Figure 4).

Bottom temperature above 12 °C reduced CPUE, and this was particularly apparent at bottom temperatures of 15−18 °C (Appendix II, Figure S2). However, it is important to note that monthly seasonality and other environmental variables may confound this trend. At lower temperatures, no effects of reduced CPUEs were apparent. In particular, CPUEs were not affected by one of the strongest upwelling events on record (observed during February 2008) (Appendix II, Figure S3). The modelling also indicated a linear negative relationship between log-transformed CPUE and bottom temperature, based on a fit to the full range of temperatures.

Overall, environmental variates explained only an additional 7% of daily variation in log-transformed CPUE with 84% of daily variation explained by the time variables of year and month which are taken to reflect (longer-term) changes in lobster abundance. When daily environmental fluctuations are averaged over a year, the effect is small or negligible on the annual CPUE index used in the current Southern Zone harvest strategy.

In addition to the analysis presented which focuses on environmental correlates, a more conventional CPUE standardisation was undertaken as part of the 2011 stock assessment for the South Australian Northern Zone. Performing a standard form of this analysis, running a GLM accounting for variation by month of the season, statistical reporting block, depth and fishing license, the standardised CPUE (as the year effect) was negligibly different from raw CPUE.

For the Victorian Western Zone, the effects of wave height, wave period, lagged wave height, and bottom temperature were similar to those in South Australia’s Southern Zone, but the effect of moon phase was weak. Of the effects modelled, more were significant when using the ‘non-screened and non-selected data’ (as reported by licence holders) than the ‘screened and selected data’ set (Appendix II).

Based on the data available, the results indicate that the environmental variables measured did not have a substantial impact on daily CPUEs. This suggests that CPUE is a reasonable index for relative abundance in South Australia’s Southern Zone fishery. In a separate analysis, the same conclusion was reached for Western Victoria (Appendix II, Section 6.6). In addition, there is no evidence from the study to suggest that the measured environmental variables contributed to the decline in CPUE observed in the fishery during 2002–09. Comparison of a season-month CPUE data series with a version of ‘standardised CPUE’ (Appendix II, supplementary data, Figure S4) visually illustrated the relatively minor impact of daily catchability. Overall, these results provide support for the newly developed harvest strategy in South Australia, which identifies CPUE as a key indicator of fishery performance and the primary biological performance indicator for setting annual TACCs.

Seasonal depletion

Definite patterns of seasonal depletion were evident in each Victorian zone. For females and males combined, the within-fishing-year trend of highest CPUE (number per potlift) early in the fishing year (November–February) decline to a minimum by June before a subsequent rise towards the end of the fishing year is consistent for the entire 34-fishing-year period from 1978–79 to 2011–12. In general, CPUE declined by June to about half the level early in the fishing-year (Appendix III, Figures 2–3). Monthly CPUE combined with monthly sex ratio for each of the seven fishing years from 2005–06 to 2011–12 (based on scientific observers recording the sex of 22,719 females and 29,519 males) show clear linear depletions for females and males combined during February–June, for females during November–May, and for males during January–June, followed by rising CPUE during July–December. These trends are consistent with the hypothesis that females are fully recruited when the fishing year opens during November, whereas males undergo protracted recruitment during July–December and are not fully recruited until January (Appendix III, Figures 3–4). Estimates of annual catchability and initial population size from deploying a within-year depletion model varied among fishing-years, but it was feasible to estimate a single catchability value over all years and estimate number of animals in the recruited population at the start of November for females and the start of January for males for each of the seven fishing-years (Appendix III, Figure 5).

The patterns of seasonal depletion detected in the Western Zone of Victoria are consistent with the hypothesis that females are fully recruited when the fishing year opens during November, whereas males undergo protracted recruitment during July–December and are not fully recruited until January. Hence, these patterns provide a basis for controlling the way the SRL-assessment model treats catchability and recruitment in Victoria. Catchability can be applied as constant for all or part of the fishing year and full recruitment of females can be applied prior to the start of the fishing season immediately following the June–October 5-month closed season for females, whereas recruitment of males is protracted during July–December. Adjustment of standardised CPUE for the effects of changing fishing efficiency over the 34-fishing-year period from 1978–79 to 2011–12 was determined from estimating annual catchability by depletion models during February–May for the sexes combined. These results suggest gear competition is the most likely factor influencing fishing efficiency (Appendix III, Figure 7).

Recruitment variation

Almost all data on puerulus settlement from South Australian and Victorian zones were positively correlated, suggesting that ocean current-driven settlement patterns into these two neighbouring states are closely related (Appendix IVb, Figure 2, Table 1). Among the four Tasmanian collector sites, PSIs showed a latitudinal trend in correlations (Appendix IVb, Table 1). Flinders Island in the north was closely correlated with the adjacent collector site of Bicheno. Both sites were also positively correlated with the collector at South Arm, the next site south. However, these correlations got successively weaker at more southerly collection sites. In particular, PSIs from Recherche Bay, the most southerly site, did not correlate with any other Tasmanian monitoring sites. Overall, these results indicated that South Australian and Victorian settlement patterns are broadly similar, but are unrelated to trends observed in north-eastern Tasmania.

Correlations between settlement and recruitment indicated spatially-varying time lags. In South Australia, PSI and recruitment to the minimum legal size (98.5 mm and 105 mm carapace length (CL) in the Southern and Northern zones, respectively) was positively correlated using a 4–5-year lag with stronger correlations in the Northern Zone (Appendix IVb, Figure 3, Table 2). In Victoria, the time period from settlement to 60 mm CL was 2 years (Appendix IVb, Figure 3, Table 3). In Tasmania, settlement into the northerly sites of Flinders Island and Bicheno were positively correlated with model recruitment (also defined at 60 m CL) to surrounding areas using a 3-year lag (Appendix IVb, Figure 3, Table 4). No relationship between settlement and recruitment could be found in any of the southernmost Tasmanian sites. Based on known growth rates of juveniles in Victorian and Tasmanian fisheries, it is estimated that the period from 60 mm CL to legal size (110 and 105 mm CL for males and females, respectively) is another 2–3 years suggesting that the total time from settlement to the fishery ranges 4–6 years. Specifically, this period is approximately 4 and 5 years in the Eastern Zone and Western Zone of Victoria, respectively, and is 6 years in northern Tasmania. In South Australia, the qR model estimates of recruitment were used for this puerulus correlation analysis, in part, because the qR model is used with the puerulus index for future biomass model projections. In this qR model, recruitment is defined as recruitment to legal size. In the length-based SRL-fishery stock assessment model, used also in South Australia and in the other states, the range of lobster length bins into which recruitment cohorts are first created varies among the three states to as low as 60 mm for the Victorian model.

Overall, this study showed that, with the exception of north-eastern Tasmania, spatial trends in PSIs are similar across most of south-eastern Australia suggesting that large-scale oceanographic processes drive settlement in South Australia and Victoria (east of Wilsons Promontory). Clearly, the ability to predict future fishery recruitment based on annual settlement indices is advantageous for fisheries management. In particular, the use of PSI to forecast future levels of modelled recruitment as an indicator of likely, or at least plausible, future changes in stock size and thus catch rates has clear advantages. Previous comparisons between puerulus catches and changes in the stock were based on CPUE data. However, since then, considerable stock rebuilding has occurred in many sampling sites. As a result, catch rates in south-eastern Australia are presently influenced more by the dynamics of the fleet and of fully-recruited cohorts, than by year-to-year variation in recruitment as in recent years when recruitment has been below the long-term average. Model estimates take account of stock rebuilding and provide a clearer index of annual changes in the number of SRLs recruiting to the harvestable biomass, based on commercial catch and effort data and length-frequency monitoring. Overall, the results indicate that puerulus monitoring is an independent and relatively robust indicator of future fishery performance and should therefore be regarded as an important guide for management of the SRL resources within south-eastern Australia.

Growth variation

Predicted annual length-increments for a sample of SRLs at any specific initial carapace length exhibited a range of length-increments represented by ‘probability density curves’ characterised by three basic shapes. Male samples were mostly ‘central-dome’ shaped (low frequency for small length-increment, high frequency for intermediate length-increment, and low frequency for large length-increment) (average near middle). Female samples were mostly exponential-decline shaped (high proportion of population exhibiting nil or negligible annual length-increment and frequency reducing with increasing length-increment), but some female samples were ‘central-dome’ shaped or ‘left-dome’ shaped (average between zero and middle length-increment). Excluding results for where and when there was inadequate sample size, mean annual length-increment generally increased from the late 1970s through the late 1990s to 2000s, and increased approximately from west to east off Victoria. During 2000s in the Western Zone and late 1990s through 2000s in the Eastern Zone, differences in mean annual length-increment for selected sizes were higher among 13 separate sites than among six separate fishing years at one of these sites. Sensitivity testing indicated a need to develop stochastic models that account explicitly for the stepped discontinuous moult-increment growth of crustaceans to improve on models based on the usual assumption of continuous growth.

The stochastic growth models performed well where annual length-increment of animals of any specific initial carapace length was ‘central-dome’ or ‘left-dome’ shaped, but ‘exponential-decline’ shape, where a high proportion of population exhibited nil or negligible annual length-increment, also predicted a small frequency of unrealistically large length-increments. Better representations of growth could be achieved by varying the usual assumption of continuous growth and developing specialised stochastic models allowing explicitly for the stepped discontinuous moult-increment growth of crustaceans to account for variation in moult increment, inter-moult period, and moult timing.

Management strategy evaluation

The results of management strategy evaluation indicate that the exploitable biomass is driven towards the target level as expected. Changes over time in natural mortality and growth are relatively inconsequential on the performance of the management procedure, and the effects of changing growth over time can be mitigated through ongoing tagging programs. In contrast, trends in catchability and recruitment will lead to management goals not being satisfied, with trends in catchability the most problematic because such trends lead to bias in stock assessment outcomes even if data sources which provide unbiased information on abundance are available for assessment purposes.

The changing of population and fishery parameters over time has been postulated for invertebrate populations (including rock lobster). However, most assessments for invertebrate stocks assume that growth and natural mortality are constant, while many assessments assume that recruitment (to legal minimum length or a pre-recruit length) is distributed about an average value. Commonly, stock assessments assume that catchability is constant over time, yet SRL in the Southern Zone and Northern Zone in South Australia can be distinguished by separate catchability parameters before and after the introduction of quota management, where the assessment for the Southern Zone showing higher catchability subsequent to quota introduction.

Anticipated impacts of time-trends in fishery processes are faster growth, decreasing natural mortality, and increasing recruitment, which lead to higher yields and less risk, whereas slower growth, increasing natural mortality, and decreasing recruitment have the opposite effects. The lower stock sizes when growth is slower, natural mortality is higher, and recruitment is decreasing are as expected, and it would have been anticipated that the management procedure would have markedly reduced catches. That the management procedure does not reduce catches sufficiently reflects the fact that the assessment is particularly biased when assumptions regarding constancy of fishery processes and parameters are violated. It might have been anticipated that the assessment could have “corrected” for these effects because it estimates each annual recruitment as an estimated parameter, and (for these simulations at least and except when catchability is changing over time) the data are largely representative of the population. The analyses in which catchability rises indicate that the assessment results are updated in the correct direction with additional data, but that the biases remain even after many years.

Benefits and Adoption

As identified in the original project proposal to FRDC, the direct benefits from the present project flow to the Victorian Rock Lobster Fishery (30% Commercial, 5% Recreational), South Australian Rock Lobster Fishery (30% Commercial, 5% Recreational), and Tasmanian Rock Lobster Fishery (30% Commercial, 0% Recreational). While direct benefits flow to the commercial and recreational fisheries, new information on SRL from the project indirectly benefit state fisheries agencies and Resource Assessment Groups involving industry, fishery manager and science representation in Victoria, South Australia and Tasmania.

The results of the project feed immediately into the SRL-fishery stock-assessment model used for determining appropriate TACCs both through enhancements to the model and improved data and information provided to the model.

Benefits flowed quickly to Victoria in that CPUE standardisation, updated growth transition matrices, and improved understanding of relationships between puerulus settlement and projections by the SRL-fishery stock-assessment model of pre-recruitment and recruitment to harvestable size were adopted for the 2012 stock assessment. These results and those of correlations between CPUE and environmental variables and outputs of management strategy evaluation will influence how Victoria, South Australia, and Tasmania adapt their fishery monitoring procedures and their approach to future stock assessments. Benefits will also flow from the review of environmental effects on lobster and crab fisheries of the world.

Further Development

Outputs from the SRL-fishery stock-model model in Victoria could be enhanced by creating model procedures that allow for direct estimation of the TACC required to meet a specified target relative to a reference year within a specified time period (or a target year). This would be for a specified level of risk for available biomass and egg production separately, where risk is expressed as percentage and where either target available biomass or egg production is expressed as a percentage of the level during the reference year.

Regarding all model output extension to stakeholders, there is a need to develop teaching aids through internet media that could be used to better inform stakeholders of benefits and developments to the SRL-assessment model as a tool for managing rock lobster fisheries.

Results from the project provide the opportunity to develop a geographic information system (GIS) for visualisation and quantification of SRL 'habitat area' within each catch and effort reporting cell for converting nominal CPUE or standardised CPUE into SRL density estimates (Quinn II and Deriso 1999) for use in the SRL-assessment model. This could involve sourcing available sea bottom type data from the Admiralty, LIDAR, universities and possibly industry for incorporation into the GIS. Victoria used SRL nominal CPUE as an index of abundance for stock assessment during the past decade up to and including the 2011 assessment (Walker, Trinnie *et al.* 2011), but changed to adoption of SRL standardised CPUE for the 2012 (Walker, Trinnie *et al.* 2012) and 2013 assessments.

In relation to environmental data, there is a need to develop a shared facility for storing bottom temperature and other environmental data sourced from various SRL monitoring systems in Victoria, South Australia, and Tasmania that ensures a common format, secure archive and ready access. There is also an ongoing need for fine-scale spatial temperature data across all fishery regions.

Selectivity of a commercial lobster pot is such that the size composition of the catch is not representative of the size composition of the SRLs in the population, and the presence of escape gaps in lobster pots alters the selectivity of the pot. The few experiments undertaken are not comparable and provide different results. Given pot selectivity is a key component of the SRL-assessment model and analysis of tag release-recapture data for growth requires correction for biases caused by pot-selectivity, it is important to have robust estimates of pot-selectivity parameters determined from several sites across the fishery. Hence, there is a need to undertake experiments to quantify better selectivity of lobster pots related to the probability of retention of SRLs depending on size of SRLs and the presence or absence of escape-gaps. Experimentation needs to consider escape-gap slot size and elevation of the bottom of the slot above the floor of a pot. Testing alternative designs for construction of scientific sampling pots that improve retention of small pre-recruits is needed to provide a better index of pre-recruit abundance. In Victoria, improved selectivity functions for selectivity and vulnerability have become essential to the Victorian assessments following the transition from excluding data on SRLs of size <legal minimum length for all early assessments to including data on SRLs of size <legal minimum length for the 2012 stock assessment.

The study demonstrated the importance of using stochastic models that reliably represent the error structure in tag length-increment data, but there remains a need to develop stochastic models that account explicitly for the stepped discontinuous moult-increment growth of crustaceans to improve on models based on the usual assumption of continuous growth. In Victoria, there is a need to understand better seasonal patterns of growth and a need to apply growth in the SRL-assessment model in a way that allows for protracted recruitment of males during July−December. This is not so important for females because they are not harvested during this period (female closed season).

Finally, recent studies (McGarvey and Matthews 2012; McGarvey, Matthews *et al.* 2009) have identified a new method to estimate mortality rate from ordinary single tag-recovery data. Extending methods first proposed in the 1950s and early 1960s, this approach, of statistically analysing the distribution of times-at-large of recaptured animals, has several important advantages over previous mark-recapture methods (e.g. MARK). As the number of animals released is never utilised, these 'recapture-conditioned' mortality estimates are unbiased by (constant) losses of SRLs from the tagged or recaptured population. Therefore ubiquitous problems of incomplete tag reporting, short-term tag shedding, or short-term tag-induced mortality do not bias these time-at-large estimates of mortality rate. Extensive ordinary single-tag recovery data are available in all three SRL State fisheries (Tasmania, Victoria, and South Australia), which have, to date, been used principally to estimate growth. The length-based SRL-assessment model (Punt, McGarvey *et al.* 2011) does not use this data source for mortality estimation. An objective for future work would be to extend the models to incorporate this rich and relatively unbiased source of information about mortality rate, a fundamental inference of all fishery stock assessment, using data from historical tag-recovery field work already undertaken by scientists and fishers.

Planned Outcomes

The original proposal to FRDC was that the project would contribute to improving assessment of SRL abundance and sustainability. In addition, the project would investigate whether declining CPUE reflect an actual decline in biomass or is a result of changing catchability or recruitment. It will improve our understanding of the environmental and catchability impacts on SRL stocks and will consequently improve the SRL-fishery stock-assessment model and improve our confidence in the modelling predictions that underpin sustainable management.

As a result of the project, there is now better understanding of CPUE in terms of how it can be affected by environmental variables and how it can be improved by data screening, selection and modelling for standardisation. Through comparing pre-recruitment trends from the enhanced SRL-assessment model with trends in puerulus settlement and patterns of within-fishing-year depletion, inter-annual variation in recruitment has major effects on total biomass. Variation in catchability is extremely difficult to measure and although there might be long-term trends in catchability associated with improved technology associated with fishing and changing fishing patterns and fishing intensity, inter-annual variation in catchability is subtle. Similarly, variation in growth inter-annually and over longer periods is subtle. In general, it is concluded that the rise and subsequent fall in biomass as predicted by the SRL-assessment model and in CPUE since the mid-1990s was a result initially of several years of above-average recruitment followed by several years of below-average recruitment. Forward projections by the SRL-assessment model when calculating appropriate TACCs account for uncertainty in future annual recruitment by randomly sampling from estimated past annual recruitments. Without improved environmental monitoring data, it is not possible at this time to determine the environmental drivers of recruitment. The best indicator available for indicating future recruitment is monitoring of puerulus settlement.

Conclusions

1. In meeting Objective 1, two methods referred to here as the Delta-X Method (combines gamma and binomial probability distribution functions) and the Tweedie Method (Tweedie probability distribution function only) were applied for CPUE standardisation of Victorian catch and effort data. The Tweedie Method statistically more elegantly incorporates zero CPUE values, but is computationally slow on computers, whereas the Delta-X Method implemented in the statistical package SAS is computationally fast and easier to use. Appropriate CPUE data screening, selection and standardisation procedures agreed through the Victorian Rock Lobster Stock Assessment Group showed in Victoria that trends in CPUE for (a) ‘unscreened’ data (as reported), (b) ‘screened’ only data, and (c) ‘screened and selected’ data were very similar to each other, indicating that screening and selection of the data did not alter the trends. However, all of these trends were very different from that in CPUE for (d) ‘screened, selected and standardised’ data. Standardised CPUE trends exhibited markedly more depletion than non-standardised CPUE trends for Victoria as a whole, for each of Western Zone and Eastern Zone, and for each of six regions.
2. In meeting Objective 2, exploration the influence of environmental variables on daily CPUE in the Southern Zone from generalised linear modelling indicated that wind speed, wind direction, wind stress and sea surface height had no statistically meaningful impact on daily CPUE. With increasing wave height, CPUEs were lower on the same day, but higher 3 or 4 days after high swells. CPUEs were also higher in the 3−4-day period prior to the 7-day full moon period, but decreased in the period after the full moon. As bottom temperatures increased, CPUE declined. Looking at the data time series, CPUEs were not affected by one of the strongest upwelling events on record (February 2008). Overall, environmental variables explained only an additional 7% of daily variation in log-transformed CPUE with 84% explained by year and month adopted for monitoring longer-term changes in SRL abundance.
3. Having met Objectives 1 and 2, it is not feasible, nor appropriate, at this time to incorporate environmental variables into CPUE standardisation for two reasons. One reason is that for the environmental variables tested, the daily fluctuations in CPUE when averaged over month or year have small or negligible effect on the pooled CPUE. The other reason is the lack of ongoing data on key environmental variables such as bottom temperature and dissolved oxygen at appropriate spatial and temporal resolutions. Hence, any detected or hypothesised effect of environmental variables on CPUE or SRL abundance will need to be handled through the SRL-fishery stock-assessment model rather than through CPUE standardisation models.
4. In meeting Objective 3 completely, patterns in Victoria’s Western Zone of declining monthly standardised CPUE, expressed in SRL number per potlift through each fishing year, are consistent with the hypothesis that females are fully recruited when the fishing year opens during November, whereas males undergo

protracted recruitment during July–December and are not fully recruited until January. These patterns created the need to modify the SRL-assessment model to provide greater flexibility in the way it handles catchability, which in turn allows for greater flexibility on application of growth and recruitment is expressed in the model.

5. In meeting objective 4 completely, with the exception of north-eastern Tasmania, spatial trends in puerulus settlement indices (PSI) are similar across most of south-eastern Australia, suggesting large-scale oceanographic processes drive settlement, notably into South Australia and Victoria (west of Wilsons Promontory). The ability to predict future fishery recruitment based on annual PSIs is an advantage for the fishery. In particular, the use of PSI to forecast future levels of modelled recruitment as an indicator of likely, or at least plausible, future changes in stock size and thus catch rates has clear advantages. Overall, the results indicate that puerulus monitoring is a relatively robust indicator of future fishery performance and should therefore be regarded as an important management tool for SRL resources within south-eastern Australia.
6. In meeting Objective 5, variation in spatial and temporal length-increment growth in SRL off the Victorian coast is remarkably high and growth is highly plastic depending on habitat and prevailing environmental conditions. General trends were detected where mean annual length-increment increased from the late 1970s, through the late 1990s, to 2000s, and increased, with exceptions, from west to east off Victoria. During the 2000s, differences in mean annual length-increment for selected sizes were higher among 13 separate sites than among 6 separate fishing years at one of these sites.
7. The present study indicates that it is not only important to have separate growth-transition matrices for the different regions of Victoria, but also to vary them over time. Hence, for each of the Portland Region, Warrnambool Region, Apollo Bay Region and Queenscliff Region, separately, a growth-transition matrix for each of the males and females is determined for each year between late the 1970s and the late 1990s and between late 1990s and 2000s, where the annual matrices determined by interpolation vary inter-annually smoothly from one period to the next. This will enable taking advantage of the flexibility of the SRL-assessment model, which includes the facility to vary growth-transition matrices spatially and temporally simultaneously.
8. In meeting Objectives 6 and 7. management strategy evaluation confirmed the importance when evaluating management procedures of accounting for the potential non-stationary fishery and biological processes, which are often represented in models by parameters fixed over time. Changes over time in natural mortality and growth do not markedly affect the performance of the management procedure, particularly given effects of changing growth over time can be mitigated through ongoing tagging programs. In contrast, trends in catchability and recruitment will lead to management goals not being satisfied, with trends in catchability the most problematic because such trends lead to bias in stock assessment outcomes even if data sources which provide unbiased information on abundance are available for assessment purposes.
9. In general, it is concluded that the rise and subsequent fall in biomass as predicted by the SRL-assessment model and indicated by CPUE since the mid-1990s resulted initially from several years of above-average recruitment followed by several years of below-average recruitment. Inter-annual variation in catchability and growth is considered subtle compared with inter-annual variation of recruitment.
10. It is not possible at this time to determine the environmental drivers of recruitment, but given the strong correlation between puerulus settlement and recruitment 4–6 years later, the main impact is environment is between egg and puerulus settlement. Hence, the best indicator available for indicating future recruitment is monitoring of puerulus settlement.

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Appendix 1: Intellectual Property

No intellectual property has arisen from the research that is likely to lead to significant commercial benefits, patents or licences. Intellectual property associated with information produced from the project will be shared equally by the Fisheries Research and Development Corporation, SARDI Aquatic Sciences, and by the Victorian Department of Primary Industries.

Appendix 2. Staff

The present project was undertaken collaboratively by staff from among SARDI Aquatic Sciences; Fisheries Victoria, Department of Environment and Primary Industries; Institute of Marine and Antarctic Studies, University of Tasmania; CSIRO Marine and Atmospheric Research; and University of Melbourne; and by consultants David K. Hobday and Dr Andrew H. Levings. Each project member was engaged part-time.

Dr Adrian J. Linnane, SARDI Aquatic Sciences

Dr Terence I. Walker, Fisheries Victoria, Department of Environment and Primary Industries

Professor André E. Punt, CSIRO Marine and Atmospheric Research

Dr Caleb Gardner, Institute of Marine and Antarctic Studies, University of Tasmania

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Dr Richard McGarvey, SARDI Aquatic Sciences

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Dr Andrew H. Levings, Consultant

Dr Mark Hemer, CSIRO Marine and Atmospheric Research

Appendix 3. Project outputs

Scientific papers published in internationally refereed journals (4)

Linnane, A., Gardner, C., Hobday, D., Punt, A., McGarvey, R., Feenstra, J., Matthews, J., and Green, B. (2010). Evidence of large-scale spatial declines in recruitment patterns of southern rock lobster *Jasus edwardsii*, across south-eastern Australia. *Fisheries Research* **105**, 163–171 (Appendix IVa).

Middleton, J. F., McGarvey, R., Linnane, A., Middleton, S. M., Teixeira, C. E. P., and Hawthorne, P. (2012). Using observations of bottom temperature to calibrate the output of an ocean model. *Journal of Marine Systems* **91**, 34–40.

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Punt, A. E., Trinnie, F. I., Walker, T. I., McGarvey, R., Feenstra, J., Linnane, A., and Hartmann, K. (2013). The performance of a management procedure for rock lobsters, *Jasus edwardsii*, off western Victoria, Australia, in the face of non-stationary dynamics. *Fisheries Research* **137**, 116–128 (Appendix VIa).

Manuscripts in preparation or submitted for publication (6)

Feenstra, J. E., McGarvey, R., Linnane, A. J., Punt, A. E., and Bean, N. (draft). Environmental influences on daily commercial catch rates of South Australia's southern rock lobster (*Jasus edwardsii*). *Fisheries Oceanography* **00**, 00–00. (1 May 2013). 30 pp. (Appendix II).

Green, B. S., Gardner, C, Jennifer D. Hochmuth, J. D. (submitted). Environmental effects on lobster and crab fisheries of the world. *Fisheries Research* **00**, 00–00. (1 May 2013). 26 pp. (Appendix VII).

Linnane, A. J., McGarvey, R., Gardner, C., Walker, T. I., and Punt, A. E. (submitted). Examining the relationship between quantified puerulus settlement and fishery recruitment in the southern rock lobster (*Jasus edwardsii*), across south-eastern Australia. (1 May 2013). 18 pp. (Appendix IVb).

Walker, T. I., Giri, K., Trinnie, F. I., and Reilly, D. J. (draft). CPUE data screening, selection and standardisation for stock assessment of southern rock lobster (*Jasus edwardsii*) in Victoria. FRDC SRL Sustainability Project 2009/047. (1 May 2013). 60 pp. (Appendix I).

Walker, T. I., Trinnie, F. I., Reilly, D. J., and Giri, K. (draft). Catchability trends determined from seasonal depletion of southern rock lobster (*Jasus edwardsii*) stocks in the Victorian fishery. FRDC SRL Sustainability Project 2009/047. Draft (1 May 2013). 28 pp. (Appendix III).

Walker, T. I., Troynikov, V. S., Trinnie, F. I., and Reilly, D. J. (draft). Spatial and temporal variation in length-increment growth of tagged rock lobster (*Jasus edwardsii*) in the Victorian fishery. (1 May 2013). 44 pp. (Appendix V).

Conference Oral Presentations, Abstracts and Posters (1)

Feenstra, J., McGarvey, R., and Linnane. A. (2011). Environmental influences on daily commercial catch rates of southern rock lobster (*Jasus edwardsii*) in South Australia. Oral presentation. Australian Society of Fish Biology, Townsville, Queensland, Australia.

Reports (3)

Linnane, A. J., Walker, T. I., Punt, A. E., Green, B. S., McGarvey, R., Feenstra, J. E., Troynikov, V. S., Trinnie, F. I., Gardner, C., Middleton, J. F., Reilly, D. J., Hobday, D. K., and Levings, A. H. (2013). Sustainability of the rock lobster resource in south-eastern Australia in a changing environment: implications for assessment and management. Draft final report to Fisheries Research and Development Corporation Project No. 2009/047. (1 May 2013.) iii + 278 pp. (SARDI Aquatic Sciences: West Beach, South Australia, Australia).

Punt, A. E. (2012). Specifications for a generalized spatial southern rock lobster model. In 'Final report to Fisheries Research and Development Corporation Project No. 2009/047'. (1 May 2013). 12 pp. (CSIRO Wealth from Oceans Flagship, Division of Marine and Atmospheric Sciences, GPO Box 1538, Tasmania 7001, Australia) (Appendix VIb).

Punt, A. E. (2012). User manual: ROCK23A. In 'Final report to Fisheries Research and Development Corporation Project No. 2009/047'. (1 May 2013). 24 pp. (CSIRO Wealth from Oceans Flagship, Division of Marine and Atmospheric Sciences, GPO Box 1538, Tasmania 7001, Australia) (Appendix VIc).

Popular articles (3)

Three popular plain English articles (two prepared by a journalist for FRDC FISH and another prepared for SRL Newsletter) are aimed at a broad audience.

Presentations

The results have been communicated to fishery managers through the annual SRL Tri-State Meeting of researchers and managers, and to fishery managers, industry and other stakeholders through various state resource assessment groups. Part of the communication strategy is the distribution to stakeholders of the present FRDC Final Report.

CPUE data screening, selection and standardisation for stock assessment of southern rock lobster (*Jasus edwardsii*) in Victoria, Australia

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Abstract

Southern rock lobster (SRL) records of catch and effort data in Victoria underwent initial processing through a series of electronic systems for data entry, secure archive, verification, validation, and summary as total catch (mass and number of SRLs), fishing effort (nominal), catch per unit effort (CPUE) (nominal), and mean mass of SRLs. Of the available records for each haul (mostly daily) of a set of lobster pots, >99% were targeted at SRL or at both SRL and giant crab, and of these >99% had non-zero CPUE. Standardised CPUE prepared for stock assessment required additional screening, selection and modelling of CPUE data from 'vessel-fishers' (vessel and fisher concatenation) contributing SRL-targeted catch during more than any two fishing-years (November–September) with ≥200 records of ≥15 potlifts per record. CPUE was standardised by a generalised linear model (GLM) with the main effects of the categorical variables of fishing-year, fishing-month, longitudinal-range, depth-range, and 'vessel-fisher' and, except vessel-fisher, their second-order interactions. For each factor level of a factor and interaction, standardised-CPUE was determined by first weighting the coefficient by the proportion of its number of observations according to the marginal-weighting procedure and then adjusting for the average effect of every other factor and interaction. GLMs with a Tweedie probability density function (pdf) fitted the data without needing to separate CPUE into zero and non-zero values as required for a Delta-X two-step model-formulation. GLMs with a log-linked gamma pdf or a log-linked Poison pdf for non-zero CPUE, adjusted each fishing-year by the proportion of non-zero CPUEs (instead of pairing with a logit-linked binomial pdf with values of 0 and 1 for zero CPUE and non-zero CPUE, respectively), provided almost identical standardised CPUE trends for the 34-fishing-year period from 1978–79 to 2011–12. Standardised-CPUE trends by fishing-year exhibited more marked reduction than nominal-CPUE trends in each of Victoria's Western Zone and Eastern Zone. CPUE standardisation with a spatial resolution of grid-cell (10 minutes of longitude) rather than region (three for each zone) and with alternative depth-ranges had negligible effect on the trends, except when including the most-easterly grid-cells of the fishery, which provided <12% of the CPUE records for the Eastern Zone and, because many of the grid-cells had missing observations, contiguous grid-cells had to be variously grouped.

Introduction

Catch per unit effort (CPUE) values calculated from commercial catch and fishing effort data submitted on routine mandatory logbook returns by fishing licence holders are used for providing an indicator of relative abundance for stock assessment of southern rock lobster (*Jasus edwardsii*) and giant crab (*Pseudocarcinus gigas*) in Victoria, Australia. Stock assessment until 2011 in each of the two management zones of the Western Zone (WZ) and Eastern Zone (EZ) used 'nominal' CPUE as an index of relative abundance for each licensing-year (1 April–31 March or for part of the licensing-year) by dividing total catch by total fishing effort (Walker *et al.* 2011). As in many fisheries, several features of lobster-pot fishing in the Victorian Rock Lobster Fishery complicate interpretation of CPUE and potentially bias CPUE as an indicator of relative abundance over short and long periods:

1. targeting between southern rock lobster (SRL) and giant crab (GC) and differences in fishing practices required between the two species;
2. differences among fishers in their levels of fishing skill, experience, and persistence;
3. differences among fishing vessels in capacity to move between fishing sites, to locate fishing sites with navigational aids available, and to operate under varying conditions;
4. differences among fishing vessels in the number of lobster pots carried (licensed) and the capacity to deploy those lobster pots most effectively;
5. differences among spatial and temporal factors such as locality, depth and season;
6. progressive adoption of new technology to increase fishing power of vessels; and

7. fluctuations and trends in market demand for SRL and GC and in profitability of the fishery.

Adjustment for some of these effects can be made through 'CPUE standardisation' by application of generalised linear models (GLM), generalised additive models (GAM), and generalised linear mixed models (GLMM) (Quinn and Keough 2002; Quinn II and Deriso 1999; Xiao *et al.* 2004). The standardisation of CPUE data provides spatial and temporal trends and patterns representative of stock abundance (Shono 2008a). The practice of standardisation of lobster-pot fishing CPUE is limited (Maunder 2001; Maunder and Starr 1995; Starr and Bentley 2005), but it is shown that CPUE standardisation improves the application of CPUE as an index of abundance for the Torres Strait rock lobster (*Panulirus ornatus*) fishery in northern Australia (Ye and Dennis 2009).

CPUE standardisation in the present study is designed to provide a standardised CPUE value as an index of relative abundance for each fishing-month for the 34-fishing-year period from 1978–79 to 2011–12 in each of the WZ and EZ and in each of three regions separately in each of the two management zones (Fig. 1a). The temporal and spatial resolution for standardisation follows the resolution required for a progressively improved SRL-fishery stock-assessment model developed in a common framework for application in Victoria (Hobday and Punt 2009; Hobday *et al.* 2005; Hobday and Punt 2007), South Australia (Linnane and Crosthwaite 2009), and Tasmania (Punt *et al.* 1997). Factors included in CPUE standardisation include fishing-year (November–September), fishing-month, longitudinal-range (composite of statistical grid-cells for 10 minutes of longitude shown in Fig. 1b), depth-range, and 'vessel-fisher' (concatenation of vessel and fisher, rather than vessel or fisher separately). Standardised CPUE was first applied in each Victorian management zone for the 2012 stock assessment (Walker *et al.* 2012) and was applied again for the 2013 stock assessment (Walker *et al.* 2013a). The change from licensing-year adopted for past assessments to fishing-year (1 or 16 November to 14 or 30 September depending on legislation for closed seasons) for the stock assessments of 2012 and 2013, was to better represent the cycle of population dynamics and fishery dynamics starting with full recruitment followed by seasonal depletion and subsequent moult-growth producing recruitment (Walker *et al.* 2013b).

Standardised CPUE is a better indicator of relative abundance than nominal CPUE, but standardisation cannot overcome some of the shortcomings of applying CPUE for stock assessment. Separate observations of CPUE computed from catch and effort reported by licence holders are not fully independent, as they are prone to the effects of gear competition, partial or full gear saturation, and autocorrelation, which may compromise inferences drawn from statistical testing dependent on the underlying assumption of the independence of observations. Standardisation cannot adjust for the effects of changes in fisher efficiency or fisher behaviour resulting from improved technology or changes in market demand or fishery management (e.g. introduction of quota management during 2001–02 in the Victorian SRL fishery), nor can it adjust for CPUE hyper-stability or CPUE hyper-depletion. Adjustment for these biases require manipulation of parameters (notably catchability) in the SRL-fishery stock-assessment model. Furthermore, inadequate attention to targeting practices (Quirijns *et al.* 2008) and spatial scale of CPUE (Campbell 2004) can lead to biases in standardised CPUE.

The present study involved five sequential procedures culminating in CPUE standardisation. Examination of data preparation processes (Procedure 1) and development of data screening processes for removing records considered erroneous or incomplete, records not targeting SRL, and records with few potlifts (Procedure 2) preceded data selection (Procedure 3), using data selection criteria based on fisher experience and minimum number of records. Data evaluation (Procedure 4) involved summarising data at various stages of Procedures 1–3 to examine spatial and temporal patterns in the data across Victoria and to compare trends in CPUE computed variously from three data sets based on progressive reduction of records from 'non-screened–non-selected' records to 'screened–non-selected' records, and then to 'screened–selected' records. CPUE standardisation applied generalised linear models only to 'screened–selected' data (Procedure 5).

Methods

Data preparation, screening and selection

Preparation and application of commercial catch and effort data for the Victorian Rock Lobster Fishery and Victorian Giant Crab Fishery collected during the 34-fishing-year period from June 1978 to September 2012 for SRL CPUE standardisation required developing data management and processing systems involving five procedures (data preparation, data screening, data selection, data evaluation, and CPUE standardisation). Added data-management fields enabled rapid extraction, summarisation and evaluation of data.

Data preparation (Procedure 1) required receiving data from licence holders and data entry, verification and stage 1 data validation checks in the Victorian State Catch and Effort System (CandE) (Fig. 2). Data verification ensured correct entry of information from licence holders on signed mandatory forms, either through double entry where the differences between data entered were computer flagged, or through visual inspection and then manually corrected. Data validation undertaken as part of computer pre-processing checked that the mandatory forms were complete and from current licence holders and registered vessels, and flagged those data values in selected fields or ratios from pairs of fields falling outside pre-set ranges. By querying the licence holders, where practical and appropriate, the data were corrected. For each of a small proportion of the records, missing catch mass or missing catch number of SRLs caught was calculated from the monthly mean mass of SRLs for the fisher or, if this is not available, for the grid-cell or region determined from the rest of the fleet. Missing potlifts were corrected from licensing information. Data archive required additional data management fields to enable rapid extraction and summarisation of data.

These data then underwent stage 2 validation in a system using the statistical and data management package SAS (version 9.3) (SAS Institute, Cary, North Carolina, USA) to produce a single SAS data file (RLCandE) in preparation for further data processing. Updating data in files CandE and RLCandE was an on-going process and the associated systems for processing the data have progressively improved over many years.

In CandE and RLCandE, each record with all associated fields related to a single haul of all the lobster pots on a particular day, with a small proportion of the lobster pots hauled more than once a day or hauled after more than one day. An important feature of file RLCande was that it contained added data fields on each record allowing for data corrections and labelling of records.

The data management and processing system also created the SAS data file RLCandEWork from RLCandE with several additional variables and data management fields for classifying and counting records (Table 1). An example of an added variable is fishing-year, which begins 1 or 16 November of one calendar year and ends 14 or 30 September of the following calendar year depending on closed-season legislation. File RLCandEWork1, created from RLCandEWork, provided corrections to the data fields ‘vessel distinguishing mark’ and ‘fisher identity’, and created a variable identifying vessel-fisher by concatenating ‘vessel distinguishing mark’ and ‘fisher identity’.

Data screening (Procedure 2) involved rejecting records with irrational data, missing information, small number of potlifts (<15 potlifts), or catch and effort averaged over more than two days. SAS data file RLCandECull provides for initial data screening and deletes records with missing key fields, bogus data, irrational data, and data repeated over more than two hauls of the lobster pots, based on averaged catch and averaged nominal fishing effort over those hauls. RLCandECull is the initial file used by the suite of SAS procedures for sub-setting the data for subsequent processing. Records specifying only SRL or both SRL and GC as the targeted species were accepted, but those specifying GC or not specifying a targeted species were screened out.

‘Data selection’ (Procedure 3) involved selecting vessel-fishers with sufficient participation in the fishery to contribute information on spatial and temporal variation in CPUE by establishing and applying criteria based on contributing data during a minimum number of separate fishing-years and on contributing a minimum number of screened records. Three sets of data selection criteria applied sequentially reduced the number of vessel-fishers without substantially reducing the number of records. These three steps producing the three data sets were (1) ‘>2-fishing-year data-contribution’ selection-criterion (i.e. records contributed in any of more than two separate fishing-years), (2) ‘>2-fishing-year data-contribution’ plus submit ≥200 records selection-criteria, and (3) ‘>5-fishing-year data-contribution’ selection-criterion. Summary data are presented for all three data sets as part of data evaluation, but only the data selected at step 2 were included in CPUE standardisation.

Data evaluation

The data management and processing system automatically generated the tables and figures shown in the present report, which not only prepared the data for subsequent CPUE standardisation, but provided ‘data evaluation’ (Procedure 4) required for development of the system. Data evaluation required summarisation of data at various stages of Procedures 1–3 to examine spatio-temporal patterns in catch, nominal effort, nominal CPUE, and numbers of vessels, fishers, vessel-fishers and records across Victoria (i.e. WZ and EZ combined). Data evaluation variously used ‘screened–non-selected’ data and ‘screened–selected’ data, where vessel-fishers contributed data for more than any two fishing-years. In addition, the data management and processing system reports various data summaries, the number (and percentage) of records with complete and missing fields, and compares trends in time-series of various types of CPUE for the three categories of ‘non-screened–non-selected’, ‘screened–non-selected’, and ‘screened–selected’ data.

Definition of CPUE

Several types of CPUE were evaluated based on alternative ways of classing CPUE, methods of determining CPUE, and level of data processing prior to computing CPUE for the purpose of the present study. Data processing provided three sets of records prepared for computing CPUE: ‘non-screened–non-selected’ records, ‘screened–non-selected’ records, and ‘screened–selected’ records; CPUE determined from ‘non-screened–non-selected’ data is referred to as “raw CPUE” by some studies, but the term is avoided in the present study.

CPUE was classed as "targeted CPUE" or "non-targeted CPUE". Records for the period from 2001–02 to 2011–12 specifying the target species as SRL or as both SRL and GC were designated as targeting SRL and records specifying the target species as GC were designated as targeting GC. Records for the period from 1978–79 to 2000–01 did not specify target species, but were designated as targeting SRL if fishing depth was <140 m and as targeting GC if fishing depth was ≥140 m. Those records classed as targeting GC were included among the 'non-screened–non-selected' records, but were rejected from the 'screened–non-selected' records and from the 'screened–selected' records.

CPUE was also classed as 'nominal CPUE' or 'standardised CPUE', with two forms of nominal CPUE ('nominal ratio-CPUE' and 'nominal mean-CPUE') where mean is the arithmetic mean. The primary 'observational CPUE' was the ratio of catch divided by fishing effort for a set of hauled lobster pots reported on a single record from a mandatory logbook return submitted by a fishing licence holder. Each of these primary observational records refer mostly to a daily haul of a set of lobster pots, but a small proportion of the records refer to a set of lobster pots hauled after a period of less than a day (a set of lobster pots can be hauled more than once a day) or hauled after a period of more than one day (up to several days). Apart from computing 'observational CPUE' (special case of 'ratio CPUE') for each record, 'ratio CPUE' was computed by summing each of catch and fishing effort separately over a selection of records and then dividing the summed catch by the summed fishing effort. 'Nominal mean-CPUE' was computed for a selection of records by averaging primary 'observational CPUE' values for a selection of records and 'standardised CPUE' was computed for a selection of records by applying generalised linear models with several explanatory variables and with primary 'observational CPUE' as the dependent variable. The units of CPUE used were kg per potlift, but number of SRLs per potlift could have been used.

CPUE standardisation

'CPUE standardisation' (Procedure 5) involved formulation of an appropriate model and determination of the probability density function (pdf) to best represent the error structure in the CPUE data. Standardisation of SRL CPUE data used 'screened–selected' data. In summary, 'screened' data excluded records with irrational or missing data, averaged catch and effort, effort not targeted at SRL or at both SRL and GC, and <15 lobster pots deployed for any haul. 'Selected' data included only screened data from vessel-fishers contributing data during >2-fishing-years and contributing a total of ≥200 for each management zone separately or the two zones combined.

CPUE standardisation aims to remove most of the annual variation in the data not attributable to changes in abundance (Maunder and Punt 2004), and the standardisation model adopted for the present study included five factors expressed as categorical variables: two temporal factors (fishing-year and fishing-month), two spatial factors (longitudinal-range and depth-range), and a single factor relating to the fishing units (vessel-fisher). The temporal factors fishing-year and fishing-month, required for input to the separate SRL stock assessment model, account for stock depletion from natural and fishing mortality as each fishing year progresses and for protracted recruitment of SRLs reaching a size exceeding the legal minimum length from length-increment associated with moult growth towards the end of the fishing-year and for males for about the first two months (November–December) of the fishing-year in Victoria. Spatial factor 'longitudinal-range' was based on selections of contiguous grid-cells of 10 minutes of longitude varied as individual grid-cell, modified-grid-cell (group of contiguous grid-cells), and region, where the six regions defined legislatively from west to east were Portland region (6 grid-cells), Port Fairy region (6), Apollo Bay region (4), Queenscliff region (8), San Remo region (12), and Lakes Entrance region (18) (Fig. 1b). The larger geographic ranges of the three most-easterly regions forming the EZ, where the SRLs tend to be sparsely distributed, had a much smaller overall catch and lower number of records than the three most-westerly regions forming the WZ. Spatial factor 'depth-range' was based on selections of two depth categories defined as above and below a depth-demarcation applied across all selections of longitudinal-range in each zone, where 40-m and 30-m depth-demarcations were adopted in the WZ, and 40-m and 25-m depth-demarcations in the EZ. The fifth factor in the standardisation model vessel-fisher accounts for differences in the fishing power of the fishing units. Many of the vessel-fishers have short periods of participation in the fishery, contribute few records, and hence provide little information through CPUE about relative abundance of the stocks. The data selection process was designed to provide a balance between reducing the number of vessel-fishers and retaining the maximum number of records available for use in CPUE standardisation.

Standardisation of the CPUE data applied generalised linear models (GLM). The GLMs are the models where the expected value of a response variable links to the linear combination of explanatory variables by a link function and the response variable takes any distribution from exponential family (McCullagh and Nelder 1983). The present study adopted two approaches to the application of GLM for CPUE standardisation.

The first approach applied the "delta-X two-step method" (Lo *et al.* 1992; Punt *et al.* 2000; Shono 2008b; Vignaux 1994; Walker and Gason 2007; Walker *et al.* 2007), which combines any one of the exponential family of four pdfs (normal, gamma, Poisson, and inverse Gaussian) log-linked paired with the binomial pdf logit linked. For each of the exponential family of four pdfs, the values of CPUE>0 were fitted to the model and, for the binomial pdf, each CPUE=0 was assigned a value of 0 and each CPUE>0 was assigned a value of 1. In this method, calculation of the standardised CPUE involved multiplying together the predicted mean determined for each of the exponential family of pdfs and the corresponding estimated probability from the binomial pdf (close to 1). In practice, the proportion of zero-CPUE values in the data was so low that the full model with the binomial-pdf logit-linked rarely converged and it was more practical to simply apply the annual proportion of non-zero CPUEs, which mostly exceeded 0.99. The method used the SAS generalised linear modelling procedure ('Proc GENMOD'), which operates readily on laptop computers.

The second approach, based on the same GLM that can explicitly handle CPUE=0 values (Candy 2003), uses the Tweedie pdf (Tweedie 1984). The Tweedie pdf is a three-parameter model generalising the exponential family of pdfs where normal, Poisson, gamma and inverse Gaussian pdfs are special cases (Dunn and Smyth 2005). The Tweedie distribution model has the power variance function:

$$Var(\mu) = \mu^{p} ,$$

where p is a power parameter that determines the shape of the Tweedie distribution models (Dunn and Smyth 2005). The Tweedie pdf can be expressed as the normal pdf when $p = 0$, Poisson pdf when $p = 1$, gamma pdf when $p = 2$, and the inverse Gaussian pdf when $p = 3$. The Tweedie pdf is not defined for $0 < p < 1$, but is defined for $1 < p < 2$ as a mixture of the Poisson and gamma pdfs (Jørgensen 1987). The Tweedie pdf handles positive-continuous data and can uniformly include large proportions of zero values (Jørgensen 1987), which is highly suitable for CPUE standardisation (Shono 2008a). Given the presence of CPUE=0 values for SRL and p falls within the range 1−2, the distribution for the CPUE data is between the Poisson and gamma pdfs.

The Tweedie method is not operational in the statistical package SAS, but is operational in the statistical package R. However, because of inadequate computing capacity of most laptop computers to analyse the large volume of data using R, a computer with a 64-bit operating system with expanded memory was required.

Standardisation of CPUE for both methods used the following model.

$$E(CPUE)_i = \mu_i ,$$

where

$$\mu_i = g^{-1}(\eta) ,$$

where $g^{-1}()$ is the inverse of the link function,

η = intercept + fishing-year + fishing-month + longitudinal-range + depth-range + vessel-fisher
fishing-year x fishing-month + fishing-year x longitudinal-range + fishing-year x depth-range
fishing-month x longitudinal-range + fishing-month x depth-range + longitudinal-range x depth-range

and where all factors and interaction terms included in this model were statistically significant, based on F-tests.

Selection of the most parsimonious model depended on following three criteria:

1. Akaike Information Criterion (AIC) calculated as $AIC = -2\ln(L) + 2K$ where L is the likelihood and K is the number of parameters estimated by the model,
2. convergence of the model, and
3. deviance / degrees of freedom, which is the dispersion index and ideally close to 1.

A standardised CPUE trend for the WZ and each of its three regions (Portland, Warrnambool, Apollo Bay) and the EZ and each of its three regions (Queenscliff, San Remo and Lakes Entrance) was determined for selected pdfs for the Delta-X two-step method and for the Tweedie method. The marginal-weighting procedure when calculating standardised CPUE avoided undue influence of combinations of factors and their interactions with limited data (exhibited in EZ but not in WZ). For each factor level of a factor and interaction, standardised-CPUE was determined by first weighting the coefficient by the proportion of its number of observations according to the marginal-weighting procedure and then adjusting for the average effect of every other factor and interaction.

Sensitivity of standardised CPUE trends to selection of spatial strata

Model choice for CPUE standardisation relating to temporal strata was limited to factors fishing-year x fishing-month, which was the resolution of monthly standardised-CPUE required for input to the SRL stock assessment model. However, choice of spatial strata defined by factor 'longitudinal-range' x factor 'depth-range' where 'longitude-range' consisted of individual or groups of contiguous grid-cells (10 minutes of longitude being the resolution of data) and depth-range consisted of two categories defined as above or below a depth-demarcation.

Sensitivity of the standardised CPUE trend in each zone to spatial resolution of the data was explored using the CPUE standardisation model formulated on the gamma pdf with log link by initially replacing the factor 'region' in the model with the factor 'grid-cell', and then in the EZ with 'modified-grid-cell'. Because there were four or more grid-cells in each region, this had the advantage of better representing finer-scale spatial resolution within each zone, but it had the disadvantage of the occurrence of nil or few primary CPUE observations for some combinations of the two-way interactions 'fishing-year' x 'grid-cell', 'fishing-month' x 'grid-cell', and 'depth-range' x 'grid-cell'. This was not a problem in the WZ, but was a major problem in the EZ. In the EZ, the problem of nil or few records for 18 grid-cells in the Lakes Entrance region and 6 grid-cells at the eastern end of the San Remo region was addressed by two approaches. One approach was to remove the 24 eastern-most grid-cells from the analysis and thereby truncate the geographic range of the EZ from grid-cells 17–54 to 17–30 (Fig. 1b); i.e. it reduced the number of grid-cells in the EZ from 40 to 14 (35% of the range). This reduced the number of 'screened–selected' records (including zero-CPUE observations) for the EZ over the 34-fishing-year period to 88%. The second approach, which avoided rejecting records, was to group selected contiguous grid-cells to create 4 amalgamated grid-cells (31–32, 33–36, 37–49, and 50–54), and then to designate the 14 unaffected grid-cells (17–30) and the 4 amalgamated grid-cells as 18 modified-grid-cells for inclusion in the CPUE standardisation model as factor 'modified-grid-cell'.

Sensitivity of the standardised CPUE trend in each zone to the choice of the values associated with the factor depth-range was examined by using two choices of depth-range: <40 m and ≥40 m (referred to as 40-m depth-demarcation) in both the WZ and EZ and <30 m and ≥30 m (30-m depth-demarcation) in the WZ and <25 m and ≥25 m (25-m depth-demarcation) in the EZ. The 40-m depth-demarcation was suggested by several professional fishers who claimed that this formed a natural demarcation based on the physiography of the fishing grounds and associated colouring of the SRLs, particularly in the WZ. The 30-m depth-demarcation in the WZ and the 25-m depth-demarcation in the EZ were based on providing for a more even number of the available records above and below each depth-demarcation.

Results

Data preparation, screening and selection

A total of 543,461 records from Victorian SRL and GC pot fishing commercial catch and effort logbook returns extracted from RLCandE were available for the 34-year period of fishing-years from 1978–79 to 2011–12. Of these records, 50,455 (9.28%) (Table 2) were rejected through 10 steps of data screening for exclusion from CPUE standardisation for several reasons:

- irrational data such as catch exceeding 550 kg for a haul of lobster pots from 15 fishers (all records for 4 fishers rejected) (rejected as erroneous or bogus data),
- returns submitted for closed month of October,
- vessel distinguishing mark, grid-cell, depth of fishing, or number of potlifts not reported (rejected as missing data),
- catch, effort and hence computed CPUE repeated for three or more days (rejected because CPUE values were averages, which reduced variance in CPUE and potentially affected the error structure of the data and violate the assumption of independent observations),
- less than 15 lobster pots hauled (rejected because the proportion of zero CPUE values and CPUE mean and variance were much higher when less than 15 lobster pots were hauled compared with when more lobster pots were hauled) (Table 3), and
- not targeting SRL or not targeting both SRL and GC (0.89% of the total number of records rejected because of targeting GC) (Table 4).

Screened records were evaluated for completeness on the basis of the number of records with completed combinations of SRL catch mass, SRL catch number, GC catch mass, potlift number, and other units of fishing effort (Table 5) and the quantities retained for various data selection criteria (Table 6). The screened data included 670 separate fishers and 824 separate vessels engaged in the fishery across the WZ and EZ during the

34-fishing-year period and from this information 1529 vessel-fishers could be computed (Table 6). Vessel-fisher is expected to be a better unit for standardisation of CPUE than either ‘fisher’ or ‘vessel’ alone, because fishing power of a vessel-fisher depends on both the attributes of the fisher (e.g. skill, persistence, targeting practice) and the attributes of the vessel (e.g. size, fishing and handling gear, and navigational aids). Screened records from 1529 vessel-fishers indicate (a) negligible zero CPUE values, (b) a CPUE mode at 0.25–0.49 kg/potlift, (c) long right-skew with high CPUE values for a small proportion of the potlifts (Fig. 3a), and vessel-fishers take a mean annual catch of <2 t, with a negligible number taking >10 t (Fig. 3b).

Participation by the vessel-fishers in the fishery since the 1978–79 fishing-year, measured as fishing effort (potlifts, days or fishing-years), varied markedly from a single day to 33 fishing-years (followed by 30, 27 and 26 fishing-years). Those vessel-fishers of low participation, including undetected errors in identity of fisher or vessel, provide little or no information on inter-annual, monthly or spatial trends, while contributing to variation in the CPUE data. Hence, excluding fishers or vessel-fishers from the analyses if they provide less than a prescribed number of has the benefit of reducing the number of vessel-fishers, without markedly reducing the number of records retained for analysis.

Data selection was applied to vessel-fisher data-contribution, across the WZ and EZ combined and to each of the WZ and the EZ separately. Adopting a ‘>2-fishing-year data-contribution’ selection-criterion (i.e. records contributed in any of more than two separate fishing-years) markedly reduced the number of vessel-fishers from 1529 to 570 (i.e. retain only 37.3%), whilst reducing the number of records from 493,197 to 433,197 (retain 87.9%) (Tables 5 and 6; Fig. 4). Applying selection criteria with longer periods of participation was avoided because it caused proportionally higher reductions in retained records. For example, a ‘>5-year data-contribution’ selection-criterion reduces the number of vessel-fishers from 1529 to 246 (retain only 16.1%), whilst reducing the number of records from 493,197 to 320,222 (retain 66.0%).

Data evaluation

Important trends are evident spatially from summary of SRL targeted records for the >2-year data-contribution selection-criterion applied to vessel-fishers. Grid-cell summaries show progressive declines from west to east across Victoria in mean annual fishing effort (Fig. 5a), mean annual catch (Fig. 5b), and mean annual number of records (Fig. 5c). Summary of data by 20-m depth-intervals show an initial increase from the 0–19-m depth-interval to peak in the 20–39-m depth-interval and then progressively decline into deeper water across Victoria in mean annual fishing effort (Fig. 6a), mean annual catch (Fig. 6b), and mean annual number of records (Fig. 6c).

Patterns of progressively higher CPUE with increasing depth throughout the 34-fishing-year period from 1978–79 to 2011–12 are evident for 20-m (Fig. 7a), 40-m (Fig. 7b), and 50-m (Fig. 7c) depth-intervals. The degree of decline over the 34-year period tends to be greatest at the middle depths. For 50-m depth-interval, for example, CPUE decline is to ~60% in the <50 m depth-interval, to ~45% in the 50–99 m depth-interval, and to ~50% in the ≥100 m depth-interval (Fig. 7c). Within the overall trend of CPUE decline over the 34-fishing-year period in Victoria, there was a slight rise followed by a decline from the mid-1990s to mid-2000s in each depth-interval.

Nominal fishing effort (Fig. 8a) and SRL catch mass (Fig. 8b) are less in the ≥40 m depth-interval than in the <40 m depth-interval. Both fishing effort and catch increased during the 1990s and then decreased during the 2000s, both <40 m and ≥40 m. Over the 34-year period, fishing effort <40 m has been about double that ≥40 m, whereas the catches have been generally similar.

Marked seasonal trends are also evident from summary of records for the >2-year data-contribution selection-criterion by vessel-fishers show marked declines in CPUE from summer to autumn and from autumn to winter (Fig. 9). Trends in CPUE from 1978–79 to 2011–12 are more widely spaced between the seasons for the Western Zone than the Eastern Zone. In the Eastern zone, the CPUE for autumn and winter are very similar after 1998–99.

Applying the >2-year data-contribution selection-criterion alone is inadequate because a large number fisher-vessel with few records are selected; at the extreme a vessel operating for one day in each of two fishing-years would be selected. Hence, in the two zones combined and in each zone separately, for a vessel-fisher to be selected, it must meet the >2-year data-contribution selection-criterion and contribute a minimum of 200 screened records.

Applying the >2-year data-contribution and ≥200 screened records selection criteria across the two zones combined selected 477 vessel-fishers. This is 31.2% of the 1529 vessel-fishers with ‘screened–non-selected’ records, and retained 77.7% of ‘non-screened–non-selected’ records and 85.7% of ‘screened–non-selected’ records (Tables 4–6). Applying these selection criteria to the WZ selected 325 vessel-fishers and to the EZ selected 156 vessel-fishers. In the WZ, this retained 21.3% of the 1529 vessel-fishers (across the WZ and EZ combined) with ‘screened–non-selected’ records, and retained 54.9% of ‘non-screened–non-selected’ records and 60.5% of 'screened–non-selected' records, and 85.3% of the 'screened and selected' records. In the EZ, this retained 10.2% of the 1529 vessel-fishers with 'screened–non-selected' records, and retained 22.2% of non-screened records, 24.5% of 'screened–selected' records, and 84.5% of the 'screened–selected' records (Tables 4–6).

The reduction in the number of records from screened–non-selected data to screened–selected data across the two zones not only reduced the number of vessel-fishers (1529 to 477), vessels (824 to 375) and fishers (670 to 317) (Table 6), but reduced the large number of fishers operating particular vessels and the large number of vessels operated by particular fishers. These marked drops in the number of vessel-fishers, vessels, and fishers can be largely explained by removing each of several vessels operated by a large number of fishers and by removing each of several fishers who operated a large number of vessels through their periods of participation in the fishery. The most extreme vessel was operated by 12 separate fishers (reduced to 4 fishers) and the most extreme fisher operate 17 separate vessels (reduced to 5 vessels). In the 'screened-selected' data-set, the percentages of vessels operated 1, 2, 3, and 4 fishers were 75, 20, 4, and 1% in the WZ and 79, 17, 3 and 1% in the EZ, and percentages of fishers operating 1, 2, 3, 4, and 5 vessels were 63, 27, 8, 1, and 0% in the WZ and 74, 17, 7, 0, and 2% in the EZ.

Comparison of trends graphically in nominal mean-CPUE and nominal ratio-CPUE among the non-screened–non-selected, screened–non-selected, and screened–selected data sets indicate negligible differences in the WZ and minor differences in the EZ (Fig. 10). This demonstrates that steps in data screening and data selection have not created biases in the data that might have biased trends before CPUE standardisation. For the screened–selected data sets only, trends in nominal mean-CPUE, nominal ratio-CPUE, and Tweedie standardised-CPUE show similar trends between nominal mean-CPUE and nominal ratio-CPUE, but both of these are very different from trends in Tweedie standardise-CPUE in each zone and each of the six regions (Fig.11).

CPUE standardisation

Models for the delta-X two-step method fitted with 'region' as the 'longitudinal-range' factor and '40-m depth-demarcation' as the 'depth-range' factor to the non-zero values of CPUE in the screened–selected data set converged for GLMs formulated from the gamma pdf log-linked, Poisson pdf log-linked and normal log-linked, but did not converge for the inverse Gaussian pdf log-linked failed to converge. The AIC together with the values of the dispersion index (deviance / degrees of freedom) and model convergence indicated that the GLM based on the gamma pdf log-linked fitted the data best, followed by the Poisson pdf, and then the normal pdf log-linked (Table 7). The results for the GLM based on the Tweedie pdf log-linked presented in Table 7 are for completion, but its AIC values are not comparable with the AIC values for other pdfs because, unlike the GLMs based on the other pdfs, the GLM based on the Tweedie pdf was adopted for fitting to zero and non-zero CPUE data simultaneously. Estimates of the Tweedie power parameter $p = 1.6204$ in the WZ and $p = 1.6286$ in the EZ are in the range $1 < p < 2$ between the Poisson and gamma probability density distributions where the distribution is closer to a gamma distribution than a Poisson distribution (Fig. 12). The Tweedie method explained 48% of the variation in the data for the WZ and 43% for the EZ.

Applying similar procedures with marginal weighting for the GLM based on the Tweedie pdf, except it was not necessary to multiply two trends as for the delta-X two-step method because the Tweedie pdf incorporates the zero CPUE values directly. Comparison of the trends in standardised CPUE determined from the GLMs based on the Tweedie pdf and delta-X two-step model-formulation from the gamma pdf log-linked and Poisson pdf log-linked were almost indistinguishable at both the levels of zone and region, but were different from the GLM based on the normal pdf log-linked (Fig.13).

The standardised CPUE trends shows a greater depletion than the nominal CPUE trend for both the WZ and EZ and for each of the six regions (Fig. 11). Apart from the Apollo Bay Region and Lakes Entrance Region, standardised CPUE begins the time series above nominal CPUE, but ends the time series below nominal CPUE. In Apollo Bay Region, higher nominal CPUE at the start of the time series is probably associated with greater restriction on the deployment of fewer lobster pots resulting in much higher CPUE compared with Portland Region and Warrnambool Region, which were included with Apollo Bay Region in CPUE standardisation for the WZ. In Lakes Entrance Region, the much higher nominal CPUE than standardised CPUE is associated with the seasonal nature of the fishery in that region; most of the catch and effort occur during the summer season resulting in higher CPUE (see Fig. 9 for overall patterns in EZ). Comparison of annual standardised CPUE by total zone, fishing-month, depth-range, and region are shown for each zone (Fig.14).

In preparation as data inputs to stock assessment, monthly total catch mass, catch number, mean mass per SRL and, for comparison purposes only, nominal CPUE computed from 'non-screened–non-selected' data and Tweedie standardised CPUE for the 34-year period from 1978–79 to 2011–12 are presented at the spatial resolutions of zone and region and temporal resolutions of fishing-year and fishing-month (Tables 8–15).

Sensitivity of standardised CPUE trends to selection of spatial strata

In the WZ, CPUE observations were available for all spatio-temporal strata except for fishing-months 8 (June) and 9 (July) during fishing-years 2006–07 and 2007–08, when temporary closed seasons were applied. The absence of primary CPUE observations for these four fishing-months were equally applicable to ‘grid-cell’ as to ‘region’ for the model factor ‘longitudinal-range’ and to ’30-m depth-demarcation’ as to ’40-m depth-demarcation’ for the factor ‘depth-range’. For stock assessment purposes, after CPUE standardisation, missing values were interpolated for each of the two months separately as the arithmetic mean of monthly standardised-CPUE over four fishing-years determined from the preceding two fishing-years (2004–05 and 2005–06) and subsequent two fishing-years (2008–09 and 2009–10). In the EZ, interpolation was not required, because these closed seasons were not applied.

In the WZ, four alternative spatial strata defined in the CPUE-standardisation model by separate combinations of ‘longitudinal-range’ x ‘depth-range’ (i.e. ‘region x 40-m depth-demarcation’, ‘region x 30-m depth-demarcation’, ‘grid-cell x 40-m depth-demarcation’, and ‘grid-cell x 30-m depth-demarcation’) provided almost identical trends, except for ‘grid-cell x 40-m depth-demarcation’, which was marginally below the trends for the other three combinations during the first seven fishing-years from 1978–79 to 1984–85 (Fig. 16a). The ‘grid-cell x 40-m depth-demarcation’ combination provided for the most parsimonious model for standardisation of CPUE data for inclusion in the stock assessment. This combination in the CPUE-standardisation model using the data at the fine-scale data-resolution of ‘grid-cell’ rather than the broad-scale data-resolution of ‘region’ for ‘longitudinal-range’ better accounts for spatial variation in CPUE across the WZ. For the model to treat each primary CPUE-observation as random from within a spatial stratum involving ‘grid-cell’ (or ‘modified-grid-cell’ as in the EZ) is more precise than treating each observation as random from within a spatial stratum involving ‘region’. In addition, the lower AIC for ‘grid-cell x 40-m depth-demarcation’ (AIC = –5,431) than for ‘grid-cell x 30-m depth-demarcation’ (AIC = –3,866) indicates that the ‘40-m depth-demarcation’ provides for a better fit to the data than does the ‘30-m depth-demarcation’. This is despite the lower AIC for ‘region x 30-m depth-demarcation’ in the model (AIC = 5,503) than for ‘region x 40-m depth-demarcation’ in the model (AIC = 186,377), which indicates that it is better to adopt the ‘30-m depth-demarcation’ than the ‘40-m depth-demarcation’ when standardising CPUE at the data resolution of ‘region’ rather than ‘grid-cell’ (Fig. 16a).

In the EZ, two alternative spatial strata defined in the CPUE-standardisation model by separate combinations of spatial factors ‘longitudinal-range’ x ‘depth-range’ (i.e. ‘region x 40-m depth-demarcation’ and ‘region x 25-m depth-demarcation’), where factor ‘longitudinal-range’ was applied to the two alternative ranges of grid-cells 17–54 (whole EZ) and grid-cells 17–30 (truncated EZ) (Fig. 1b). These combinations provided remarkably similar trends for the whole EZ between ‘region x 40-m depth-demarcation’ (AIC = 46,570) and ‘region x 25-m depth-demarcation’ (AIC = –50,887) and for the truncated EZ between ‘region x 40-m depth-demarcation’ (AIC = –56,960) and ‘region x 25-m depth-demarcation’ (AIC = –55,711), where the CPUE-standardisation models fit to the data better with a ‘25-m depth-demarcation’ than a ‘40-m depth-demarcation’ for the whole EZ, but better with a ‘40-m depth-demarcation’ than a ‘25-m depth-demarcation’ for the truncated EZ. However, the trends between the whole EZ and truncated EZ were markedly different. This indicates the importance of including the data from those areas where SRLs are sparsely distributed in the eastern areas of the EZ, when determining a standardised-CPUE trend for the entire EZ (Fig. 16b).

In the EZ, two additional spatial strata defined in the CPUE-standardisation model by separate combinations of spatial factors ‘longitudinal-range’ x ‘depth-range’ (i.e. ‘modified-grid-cell x 40-m depth-demarcation’ and ‘modified-grid-cell x 25-m depth-demarcation’), where factor ‘longitudinal-range’ was applied to the range of grid-cells 17–54 (whole EZ). These combinations also provided remarkably similar trends for the whole EZ between the ‘40-m depth-demarcation’ (AIC = –59,289) and ‘25-m depth-demarcation’ (AIC = –58,319), except the CPUE-standardisation models fitted the data better with a ‘40-m depth-demarcation’ than a ‘25-m depth-demarcation’. The trends for the whole EZ applied with ‘longitudinal-range’ factor ‘modified-grid-cell’ and ‘region’ were similar, but with notable differences for the periods from 1978–79 to 1980–81 and from 2003–04 to 2005–06, indicating that the best option for CPUE standardisation in the EZ is to apply ‘modified-grid-cells’ to the whole zone (Fig. 16c).

Discussion

The need to define the efficiency of a fishing vessel as its fishing power relative to that of a standard fishing vessel (Beverton and Holt 1957; Gulland 1956) was recognised well in advance of CPUE standardisation using GLMs accounting for multiple factors (Maunder and Punt 2004). Most experience with CPUE standardisation is for populations of harvested teleost, shark and invertebrate species for fishing methods other than lobster-pot fishing. Published examples are mostly for demersal otter trawl (Chatterton 1996; Goñi *et al.* 1999; Kulka *et al.* 1996; Salthaug and Godø 2001; Walker and Gason 2007; Walker *et al.* 2007). Other examples include beam trawl (Large 1992), gillnet (Punt *et al.* 2000), long line (Bradford 2001; Campbell 2004; Fonteneau and Richard

2003; Goodyear 2003; Hinton and Nakano 1996; Kimura 1981; Nakano 1997), and purse seine (CPUE associated with spotter planes) (Lo *et al.* 1992).

The approach of the present study was to fit and to test GLMs based on any one of the exponential family pdfs (normal, gamma, Poisson, Inverse Gaussian and Tweedie) with a log-link function to the CPUE data. Models applying a log-link function with normal (Kimura 1981; Large 1992), gamma (Goñi *et al.* 1999; Punt *et al.* 2000) and inverse Gaussian pdfs cannot handle zero CPUE values whereas Poisson and Tweedie pdf can handle zero CPUE values.

In many studies zero CPUE values are ignored or adjusted by the addition of a small constant (Bradford 2001; Punt *et al.* 2000). These practices were avoided in the present study because the magnitude of the added constant affects standardised CPUE trends (Shono 2008a). Another approach, sometimes taken to reduce the proportion of zero CPUE values, is to aggregate catch over larger units of fishing effort (Punt *et al.* 2000) from say the lobster pots hauled each day to a larger unit such as all lobster pots hauled during each month. This approach can reduce the standard errors on point estimates and reduce noise, if the standardised CPUE trends are inputs to stochastic fishery assessment models, but this reduces the resolution of the data.

The approach of the present study was to work with the data at the collection resolution and to explore the variability in the data at that resolution rather than bulk the records of data over more than one haul of the set of lobster pots to avoid zero CPUE values. Although only less than 1 per cent of the records produced zero CPUE values, the present study explored two approaches to including zero CPUE values in statistical modelling. The Tweedie method statistically more elegantly incorporates zero CPUE values, but presently is computationally slow on the most powerful laptop computers, whereas the delta-X two-step method, implemented in the statistical package SAS, is computationally fast on standard laptop computers and easier to use. However, given the Tweedie method works with distributions between the specific distributions available in SAS ‘Proc GENMOD’, the method is likely to be more precise. Delta-X two-step method indicated that GLMs based on the log-linked gamma pdf fitted the CPUE>0 values better than GLMs based on the log-linked Poisson pdf, whereas the Tweedie method indicated that a distribution between Poisson and gamma best fit the data, but was closer to the gamma distribution than the Poisson distribution (i.e. p is closer to 2 than to 1 in both the WZ and the EZ).

In theory, these model formulations could be extended to include environmental variables, such as bottom water temperature (Su *et al.* 2008a; Su *et al.* 2008b), dissolved oxygen, and river flow, but this is not feasible at his time because the lack of continuity of broad-scale data at spatial and temporal resolutions compatible with the CPUE data. It is likely to be more feasible to consider correlation of standardised CPUE with astronomical cycles, such as moon phase (at fine temporal resolution) (Appendix II) and magnetic activity in response to solar emissions and with indices related oceanographic events such the Bonney Upwelling. Exploring correlations with indices of climate cycles, such as the El Niño Southern Oscillation, Pacific Decadal Oscillation, or the Indian Ocean Dipole may also be fruitful.

Further enhancement to the data for use in the SRL stock assessment model could be achieved by quantifying SRL ‘habitat area’ within two depth intervals (<40 m and ≥40 m) of each catch and effort reporting grid-cell of 10 minutes of longitude (Figure 1b) by converting standardised CPUE into relative SRL density estimates (Quinn II and Deriso 1999). This would involve sourcing available sea-bottom-type data for incorporation into a geographic information system used interactively with the CPUE data.

Conclusions

Four key conclusions are drawn from the present study. (1) In the Victorian rock lobster fishery, considerable pre-processing of data leading to data screening and data selection is required before undertaking CPUE standardisation. (2) The model used to standardise CPUE needs to include the main effects of the categorical variables of fishing-year, fishing-month, longitudinal-range, depth-range, and vessel-fisher and, except vessel-fisher, their second-order interactions, where the longitudinal-range factor is at the spatial resolution of grid-cell in the WZ and ‘modified-grid-cell’ in the EZ, and the depth-range factor is at the spatial resolution of 40-m depth-demarcation. (3) A GLM with log-linked gamma pdf or log-linked Poisson pdf for non-zero Poisson CPUE adjusted by proportion of non-zero CPUE observations fits well to the data, but a GLM with a Tweedie pdf fits to the data to produce similar trends, but can include large proportions of zeros without needing to separate the data into zero and non-zero CPUE components. (4) Standardised CPUE trends for the 34-year period from 1978–79 to 2011–12 exhibits more marked reduction than nominal CPUE trends in each of Victoria’s two fishery management zones and six regions.

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Table 1. Data selection variables adopted for counting records and accumulating values

SRL, southern rock lobster; GC, giant crab; C, count; P, present; A, absent; C, corrected; U, uncorrected; Pots, lobster pots; PL, potlifts (nominal).

Categorial variables	Continuous catch & effort variables	Count	Present or Absent	Corrected or Uncorrected	Species or lobster pot	Variable
		C	P	C, U	SRL, GC, Pot	Kg, No, PL
All records	Total number of records	C	P	U	All	Al
	Total number of records with Pots	C	P	U	Pot	PL
PersonNo	Total number of records with corrected Pots, corrected SRL Kg, & corrected SRL No.	C	P	C	PRL	Cm
Reg	Total number of records with corrected SRL Kg & corrected SRL No.	C	P	C	SRL	Cm
RegPerson	Total number of records with corrected SRL Kg	C	P	C	SRL	Kg
	Total number of records with corrected SRL No.	C	P	C	SRL	No
Zone_q	Total number of records with corrected Pots, corrected SRL Kg (zero), & corrected SRL No (zero)	C	A	C	SRL	Cm
Area_q	Total number of records with uncorrected Pots, uncorrected SRL Kg, & uncorrected SRL No.	C	P	U	SRL	Cm
Depth catgeory	Total number of records with uncorrected Pots, uncorrected SRL Kg	C	P	U	SRL	Kg
Target	Total number of records with uncorrected Pots, uncorrected SRL No.	C	P	U	SRL	No
	Total number of records with uncorrected Pots, uncorrected GC Kg & SRL No.	C	P	U	GCb	Cm
FsYr	Total number of records with uncorrected Pots, uncorrected GC Kg	C	P	U	GCb	Kg
FsMn	Total number of records with uncorrected Pots, uncorrected GC No.	C	P	U	GCb	No

Table 2. Number of records sequentially rejected through data screening steps for the 34-year period of fishing years from 1978–79 to 2011–12

Fishing year, period from 1 or 16 November to 14 or 30 September (depending on legislation); SRL, southern rock lobster; GC, giant crab; CPUE, catch mass per unit effort data; area, 10 grid-cell minutes of longitude; all records specify Fisher, Year, Month, Day, Target species, and Zone.

Screening criterion	Step	Records included		Records excluded	
		Number	Per cent	Number	Per cent
All records		543461	100.00		
without records from 15 fishers (selected records for 11 & all records for 4) rejected because of irrational data or missing key data fields	1	542125	99.75	1336	0.25
& without records for October	2	541636	99.66	489	0.09
& without records with missing vessel distinguishing mark	3	541149	99.57	487	0.09
& without records with missing information on area grid cell	4	535216	98.48	5933	1.09
& without records with missing information on depth	5	529782	97.48	5434	1.00
& without records with missing information on catch mass (i.e. catch alternatively reported only as catch number)	6	516271	95.00	13511	2.49
& without records not targeting SRL or not targeting both SRL & GC	7	511537	94.13	4734	0.87
& without records with missing information on number of pots	8	511474	94.11	63	0.01
& without records where no. of pots set is <15 because of high cpue mean, variation and proportion of zeros (see Table 3)	9	501846	92.34	9628	1.77
& without records from 11 fishers (selected records for 9 & all records for 2) rejected because CPUE is averaged over 3 or more days	10	493006	90.72	8840	1.63
Total records excluded by the screening process				50455	9.28

Data source: Fisheries Victoria CandE Database (11 January 2013)

Table 3. CPUE by lobster pot number range from 1978–79 to 2011–12

CPUE, catch mass per unit effort data partially screened (Table 2 Step 8), Sd, standard deviation.

Lobster pots set no. range	Number of records			% zero CPUE	CPUE (kg/potlift)			
	Non-zero CPUE	Zero CPUE	Total		Mean	Sd	Minimum	Maximum
1–4	437	463	900	51.4	1.18	2.38	0.00	34.00
5–9	1829	539	2368	22.8	0.79	1.30	0.00	19.98
10–14	5578	782	6360	12.3	0.71	0.89	0.00	10.80
15–19	14037	843	14880	5.7	0.51	0.54	0.00	12.33
20–24	26930	781	27711	2.8	0.59	0.56	0.00	7.88
25–29	21544	352	21896	1.6	0.52	0.47	0.00	9.79
30–34	33527	486	34013	1.4	0.55	0.54	0.00	9.38
35–39	21287	289	21576	1.3	0.50	0.50	0.00	9.47
40–44	35836	358	36194	1.0	0.54	0.50	0.00	10.16
45–49	43907	370	44277	0.8	0.58	0.51	0.00	10.18
50–99	279642	1803	281445	0.6	0.56	0.43	0.00	9.50
100–149	18265	527	18792	2.8	0.53	0.39	0.00	5.36
≥150	1053	9	1062	0.8	0.50	0.37	0.00	2.54
Total	503872	7602	511474	1.5	0.56	0.50	0.00	34.00

Data source: Fisheries Victoria CandE Database (11 January 2013)

Table 4. Number and per cent of records variously non-screened, screened and selected by zone from 1978–79 to 2011–12

Fishing year, period from 1 or 16 November to 14 or 30 September (depending on legislation); all records specify vessel, fisher, fishing year, fishing month, day, target sp rock lobster; GC, giant crab.

Selected data set	All records (no. including zero catch)	Per cent of all records		
		Non-screened	Screened	Screened & selected
'Non-screened–non-selected' records those targeting SRL or both SRL and GC				
Zones combined				
All records	543461	100.0		
& with only records targeting SRL or targeting both SRL & GC	538606	99.1		
Western Zone				
All records	381192	70.1		
& with only records targeting SRL or targeting both SRL & GC	376399	69.3		
Eastern Zone				
All records	162269	29.9		
& with only records targeting SRL or targeting both SRL & GC	162207	29.8		
'Screened–non-selected' records and application of alternative selection criteria				
Zones combined				
All screened records before selection	493006	90.7	100.0	
& >2 fishing years of data contributed by each vessel-fisher	433197	79.7	87.9	
& 200 records or more	422524	77.7	85.7	
& >5 fishing years of data contributed by each vessel-fisher	320222	58.9	65.0	
Western Zone				
All screened records before selection	350032	64.4	71.0	100.0
& >2 fishing years of data contributed by each vessel-fisher	306220	56.3	62.1	87.5
& 200 records or more	298495	54.9	60.5	85.3
& >5 fishing years of data contributed by each vessel-fisher	224387	41.3	45.5	64.1
Eastern Zone				
All screened records before selection	142974	26.3	29.0	100.0
& >2 fishing years of data contributed by each vessel-fisher	124654	22.9	25.3	87.2
& 200 records or more	120761	22.2	24.5	84.5
& >5 fishing years of data contributed by each vessel-fisher	93604	17.2	19.0	65.5

Data source: Fisheries Victoria CandE Database (11 January 2013)

Table 5. Number of screened and selected records by zone with and without records corrected for missing catch and effort data fields from 1978–79 to 2011–12

Fishing year, period from 1 or 16 November to 14 or 30 September (depending on legislation); SRL, southern rock lobster; GC, giant crab; Pots, lobster pots; all records specify Vessel, Fisher, Year, Month, Day, Target species, and Zone.

Selected data set	Number of included records corrected or uncorrected for missing potlifts, SRL mass or SRL number								
	Corrected records included		Corrected records excluded						
	Records	SRL zero catch	Lobster pots	Pots SRL Kg SRL No	Pots SRL Kg	Pots SRL No	Pots GC Kg GC No	Pots GC Kg	Pots GC No
Quantities expressed in numbers									
Zones combined									
All screened records before selection	493006	5572	492094	477715	486795	477849	3404	12007	3539
& >2 fishing years of data contributed	433197	4489	432384	421039	428112	421140	3189	10475	3314
& 200 records or more	422524	4314	421726	411156	417626	411256	3105	9909	3226
& >5 fishing years of data contributed	320222	3060	319678	311647	316750	311712	2696	6640	2811
Western Zone									
All screened records before selection	350032	2986	349477	339948	346660	339989	3376	11609	3510
& >2 fishing years of data contributed	306220	2408	305748	298122	303470	298153	3171	10175	3295
& 200 records or more	298495	2311	298052	290979	295868	291010	3087	9626	3207
& >5 fishing years of data contributed	224387	1539	224107	219104	222645	219124	2693	6589	2807
Eastern Zone									
All screened records before selection	142974	2586	142617	137767	140135	137860	28	398	29
& >2 fishing years of data contributed	124654	2040	124325	120891	122371	120961	3	251	4
& 200 records or more	120761	1951	120441	117380	118576	117449	3	243	4
& >5 fishing years of data contributed	93604	1487	93374	90940	91941	90985	3	150	4
Quantities expressed as per cent									
Zones combined									
All screened records before selection	100.0	1.1	99.8	96.9	98.7	96.9	0.7	2.4	0.7
& >2 fishing years of data contributed	87.9	0.9	87.7	85.4	86.8	85.4	0.6	2.1	0.7
& 200 records or more	85.7	0.9	85.5	83.4	84.7	83.4	0.6	2.0	0.7
& >5 fishing years of data contributed	65.0	0.6	64.8	63.2	64.2	63.2	0.5	1.3	0.6
Western Zone									
All screened records before selection	71.0	0.6	70.9	69.0	70.3	69.0	0.7	2.4	0.7
& >2 fishing years of data contributed	62.1	0.5	62.0	60.5	61.6	60.5	0.6	2.1	0.7
& 200 records or more	60.5	0.5	60.5	59.0	60.0	59.0	0.6	2.0	0.7
& >5 fishing years of data contributed	45.5	0.3	45.5	44.4	45.2	44.4	0.5	1.3	0.6
Eastern Zone									
All screened records before selection	29.0	0.5	28.9	27.9	28.4	28.0	0.0	0.1	0.0
& >2 fishing years of data contributed	25.3	0.4	25.2	24.5	24.8	24.5	0.0	0.1	0.0
& 200 records or more	24.5	0.4	24.4	23.8	24.1	23.8	0.0	0.0	0.0
& >5 fishing years of data contributed	19.0	0.3	18.9	18.4	18.6	18.5	0.0	0.0	0.0

Data source: Fisheries Victoria CandE Database (11 January 2013)

Table 6. Quantities for screened and selected records for each zone with and without records corrected for missing catch and effort data fields from 1978–79 to 2011–12

Fishing year, period from 1 or 16 November to 14 or 30 September (depending on legislation); SRL, southern rock lobster; GC, giant crab; CPUE, screened catch mass per unit effort data; corrected, missing data corrected.

Selected data set	Fishers	Vessels	Quantities summed over all records corrected and uncorrected for missing potlifts, SRL mass or SRL number									
			Vessel-fishers	SRL mass (tonne)	SRL number ('000)	GC mass (tonne)	Potlifts ('000)	Soak time ('000)	Soakpots ('000)	Mean SRL mass (kg)	SRL CPUE (kg/potlift)	SRL CPUE (no/potlift)
Quantities expressed in numbers												
Zones combined												
All screened records before selection	670	824	1529	14880	15546	217	26822	577	22689	0.96	0.55	0.58
& >2 fishing years of data contributed			570	13212	13840	187	23739	506	19619	0.95	0.56	0.58
& 200 records or more	317	375	477	12794	13436	174	23216	494	19112	0.95	0.55	0.58
& >5 fishing years of data contributed			246	9774	10297	122	17743	373	14178	0.95	0.55	0.58
Western Zone												
All screened records before selection			1109	12532	13422	213	21279	408	17648	0.93	0.59	0.63
& >2 fishing years of data contributed			391	11136	11958	185	18803	356	15131	0.93	0.59	0.64
& 200 records or more	238	259	325	10804	11622	172	18381	347	14703	0.93	0.59	0.63
& >5 fishing years of data contributed			163	8250	8907	123	13950	259	10668	0.93	0.59	0.64
Eastern Zone												
All screened records before selection			569	2348	2124	4	5543	169	5041	1.11	0.42	0.38
& >2 fishing years of data contributed			196	2012	1822	2	4841	148	4399	1.10	0.42	0.38
& 200 records or more	124	129	156	1901	1728	2	4704	143	4275	1.10	0.40	0.37
& >5 fishing years of data contributed			92	1495	1360	1	3718	111	3454	1.10	0.40	0.37
Quantities expressed as per cent												
Zones combined												
All screened records before selection	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0			
& >2 fishing years of data contributed			37.3	88.8	89.0	86.3	88.5	87.8	86.5			
& 200 records or more	47.3	45.5	31.2	86.0	86.4	80.1	86.6	85.6	84.2			
& >5 fishing years of data contributed			16.1	65.7	66.2	56.1	66.2	64.6	62.5			
Western Zone												
All screened records before selection			72.5	84.2	86.3	98.3	79.3	70.7	77.8			
& >2 fishing years of data contributed			25.6	74.8	76.9	85.1	70.1	61.7	66.7			
& 200 records or more	35.5	31.4	21.3	72.6	74.8	79.0	68.5	60.2	64.8			
& >5 fishing years of data contributed			10.7	55.4	57.3	56.6	52.0	45.0	47.0			
Eastern Zone												
All screened records before selection			37.2	15.8	13.7	1.7	20.7	29.3	22.2			
& >2 fishing years of data contributed			12.8	13.5	11.7	1.0	18.0	25.6	19.4			
& 200 records or more	18.5	15.7	10.2	12.8	11.1	1.0	17.5	24.8	18.8			
& >5 fishing years of data contributed			6.0	10.0	8.7	0.6	13.9	19.2	15.2			

Data source: Fisheries Victoria CandE Database (11 January 2013)

Table 7. Statistical quantities for evaluation of model fits to CPUE data based of different pdfs

CPUE, screened and selected catch mass per unit effort data for vessel-fishers contributing data during the period from 1978–79 to 2009–11 in >2 fishing years and ≥200 records; pdf, probability density function; Df, degrees of freedom; AIC, Akaike Information Criterion; AIC = –2Ln(L) + 2K where L is likelihood and K is the number of parameters estimated by a model (lowest AIC value indicates the most parsimonious model structure); K for Binomial pdf excludes vessel-fisher factor and all interaction terms; na, no analysis. Binomial and Tweedie pdfs are included for completion, but their AIC values cannot be compared with the AIC values for other pdfs because the model fitted with Binomial pdf was fitted to 0 and 1 values and the model fitted with Tweedie pdf was fitted to zero and non-zero CPUE values, whereas and models based on other pdfs were fitted to only non-zero CPUE values.

Statistical item	Model variable or pdf	Link	Victoria	Zone	
				Western	Eastern
No. of observations	Non-zero		418210	296184	118810
	Zero		4314	2311	1951
	Total		422524	298495	120761
	Non-zero proportion		0.990	0.992	0.984
No. of parameters	Intercept		1	1	1
	Fishing year		33	33	33
	Fishing month		9	9	9
	Region		5	2	2
	Depth class		1	1	1
	Vessel-fisher		476	324	155
	Fishing year x Fishing month		297	297	297
	Fishing year x Region		66	66	66
	Fishing year x Depth class		33	33	33
	Fishing month x Region		45	18	18
	Fishing month x Depth class		9	9	9
	Region x Depth class		5	2	2
	Total (K)		980	795	626
Model convergence	Normal	Log	Yes	Yes	Yes
	Gamma	Log	Yes	Yes	Yes
	Poisson	Log	Yes	Yes	Yes
	Inverse guassian	Log	No	No	No
	Binomial	Logit	Yes	Yes	Yes
	Tweedie	Log	Yes	Yes	Yes
Deviance/Df	Normal	Log	0.1050	0.1105	0.0861
	Gamma	Log	0.2914	0.2580	0.3612
	Poisson	Log	0.1391	0.1373	0.1370
	Inverse guassian	Log	3.4084	2.5831	5.2899
	Binomial	Logit	0.1094	0.0853	0.1564
	Tweedie	Log	na	0.2166	0.2782
Log-likelihood Ln(L)	Normal	Log	-119886	-92187	-22345
	Gamma	Log	19078	-2080	26648
	Poisson	Log	-331747	-243099	-85560
	Inverse guassian	Log	-298514	-221743	-59247
	Binomial	Logit	-22770	-12518	-22345
	Tweedie	Log	na	26801	-11562
AIC	Normal	Log	241731	185964	45941
	Gamma	Log	-36196	5749	-52044
	Poisson	Log	665455	487788	172371
	Inverse guassian	Log	598989	445075	119745
	Binomial	Logit	45541	25036	44689
	Tweedie	Log	na	55191	-21871

Data source: Fisheries Victoria CandE Database (11 January 2013)

Table 8.1.1. Monthly catch mass during fishing years from 1978–79 to 2011–12 for each zone

Data: non-screened and non-selected.

Fishing year	Catch (kg) for each month									
	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug–Sep
Western Zone										
1978–79	55357	90916	93799	68268	71891	37376	14367	6581	7129	39837
1979–80	65296	62934	84152	76129	57654	35773	11961	5851	10466	42518
1980–81	80368	102149	108194	94778	64157	35320	13684	4356	8107	37752
1981–82	71355	87133	101813	77049	65888	31988	8866	6167	9442	38950
1982–83	65866	90728	71180	74583	54778	38157	15064	2836	8907	38395
1983–84	54566	86529	84355	75078	45951	23465	14655	3187	5871	26885
1984–85	47145	58803	85601	77878	56267	30786	13290	3839	5406	26801
1985–86	57324	55968	57646	52618	48857	19887	11365	3389	5566	32369
1986–87	50207	56936	58576	53864	52719	34686	9378	4555	7699	22573
1987–88	23385	67893	72751	57370	55822	29895	13390	4071	6635	14101
1988–89	20468	55443	55604	49560	48499	28903	13828	5672	9688	16101
1989–90	25320	57966	67680	51277	57866	27705	12017	5360	9334	16906
1990–91	18704	50347	60243	51283	48212	30924	20071	6252	15625	14916
1991–92	27545	61815	72252	68150	65502	45091	29533	9755	11582	17230
1992–93	22170	60379	87452	54081	63935	47661	25986	7903	16398	21908
1993–94	36394	69238	64830	79244	85570	40296	21003	13335	16364	21954
1994–95	29973	82152	87992	68865	55013	31909	29948	12870	13973	22351
1995–96	28762	67502	83364	74345	64841	29770	29345	9519	14928	20256
1996–97	25148	73109	71089	68861	51968	37666	24385	11137	16316	22345
1997–98	32690	88903	94329	61631	61816	39963	26440	12505	16161	31670
1998–99	37517	83606	89420	76631	75692	57154	30968	10858	18694	35243
1999–00	42608	78172	81922	88492	70384	54437	27310	9958	24060	43481
2000–01	52128	85556	107030	89465	59935	40095	34048	9297	22054	25300
2001–02	33271	72801	90456	65633	53122	46710	29668	3981	11349	31139
2002–03	38711	76731	89159	66797	42720	39710	34774	5633	11133	24324
2003–04	44575	70125	74295	76276	62250	46536	30672	6645	13072	36147
2004–05	35420	68871	74912	56666	49855	43646	26439	10091	8985	33180
2005–06	30390	54746	82016	66676	47810	17951	12546	4342	9806	31420
2006–07	26077	57147	57570	61480	46010	36130	14855	0	0	36656
2007–08	32070	51362	57695	45915	44021	26153	14780	0	0	16641
2008–09	17412	44298	50321	38924	31846	17629	13052	3830	4707	13090
2009–10	19004	40016	42332	36451	30546	19482	17197	7136	9356	17339
2010–11	19858	36751	52458	31762	30057	23200	10396	3810	14327	31747
2011–12	20826	47052	39536	36398	24280	13091	5836	2616	14222	28651
Eastern Zone										
1978–79	25055	21399	27085	14643	12643	7897	3750	880	3322	22398
1979–80	16183	20163	19447	19286	9177	7650	3326	374	3760	16187
1980–81	23468	22635	24815	19547	11263	6585	3957	789	3685	16678
1981–82	16799	25139	23405	21184	13667	5966	1985	933	4203	17608
1982–83	23829	25755	19997	20367	14118	7638	3676	1840	5419	20534
1983–84	17976	24439	23825	21580	13296	8419	3867	1062	3856	18143
1984–85	20547	22173	20114	15013	12915	6854	2151	565	2024	10569
1985–86	19868	19501	17025	11172	7725	4307	2395	554	1887	10243
1986–87	12966	14426	12384	11190	8212	3361	1104	839	2859	10399
1987–88	7933	16607	16305	9618	8184	3145	1270	668	2361	3893
1988–89	6542	13469	13404	8053	6572	4165	900	558	3636	6282
1989–90	9385	16618	15971	11784	10550	5197	1612	633	3681	7963
1990–91	7394	14183	14237	10356	7030	3423	1790	704	5062	7350
1991–92	6928	11938	9491	10462	8278	4115	1863	984	3713	6791
1992–93	5056	11575	13750	8301	8647	5882	2395	1151	5839	6791
1993–94	9023	14763	14196	12159	9986	3705	1663	1759	4724	6741
1994–95	5717	14861	13721	10671	6932	5541	3300	1221	4486	5555
1995–96	3876	8920	10548	9465	7664	3348	1912	1644	4616	4733
1996–97	3137	9833	9711	9494	7015	3958	2854	2440	4898	6453
1997–98	7871	13424	11052	7543	6734	3915	2498	1737	4734	6806
1998–99	4457	11714	11905	9298	5782	4883	2558	1785	5550	9337
1999–00	6572	12023	12012	12536	7494	4903	1627	1887	5279	10298
2000–01	9617	14599	11700	8272	4772	3575	2425	1884	7223	8582
2001–02	4766	10377	10663	5487	5273	3163	1271	453	4170	7831
2002–03	4830	9941	8570	6769	3979	4597	2111	500	3855	7270
2003–04	4477	11109	8572	6132	5450	2492	2305	886	3160	10958
2004–05	5487	9072	10338	5220	5464	3507	1957	1409	2724	9590
2005–06	4035	10292	10267	7140	5383	970	1091	1077	3004	9019
2006–07	3897	9448	8305	8323	6192	3163	1940	1017	3216	8351
2007–08	4617	9683	6833	5149	5055	2315	1359	566	4237	6154
2008–09	2257	7013	7513	3882	5247	2852	1772	982	3288	4667
2009–10	3368	8116	7850	5930	4304	2435	2061	1601	6338	13181
2010–11	5085	11581	12017	5781	3580	3310	3024	1055	5870	14364
2011–12	5670	13230	12125	4479	2559	2901	2745	1085	7236	9601

Data source: Fisheries Victoria CandE Database (11 January 2013)

Table 8.2.1 Monthly catch mass during fishing years from 1978–79 to 2011–12 for each region

Data: non-screened and non-selected.

Fishing year	Catch (kg) for each month									
	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug–Sep
Portland Region										
1978–79	24433	40528	48360	30005	38249	19674	5207	1869	4774	22554
1979–80	27325	25935	37873	34052	31220	16787	2704	2564	5844	32054
1980–81	46975	60280	63826	62319	37536	18064	4776	2602	5527	22691
1981–82	33618	41315	53681	41455	39605	17550	3552	1861	6567	25295
1982–83	28540	35218	42176	45863	37316	23780	7300	682	6140	27251
1983–84	25695	39512	43174	36111	23377	10779	2608	362	3664	14937
1984–85	23938	29193	35913	32992	27192	15419	3440	558	2890	15296
1985–86	27751	26934	28986	23600	24054	12423	4198	945	3500	18605
1986–87	32389	34997	31821	25100	23041	15253	2392	755	4062	10609
1987–88	14254	41695	36802	28582	28626	15564	4165	1889	3353	7491
1988–89	11703	31631	29019	25394	27646	14107	5799	1487	5393	9338
1989–90	14820	32396	38732	29756	34297	18021	6882	2259	6112	9799
1990–91	10616	27079	32910	30352	31963	19396	10441	2470	9345	10242
1991–92	17254	39474	43708	42007	38750	26743	16610	4480	7156	10124
1992–93	11935	35096	45655	29815	30672	25443	14156	3463	7653	10811
1993–94	20493	38852	35808	38240	39777	21332	11367	6214	9361	13106
1994–95	15873	47418	47136	38833	32585	19027	17340	6130	9765	14848
1995–96	19855	44618	47794	44907	43157	20645	16622	4258	8665	11885
1996–97	17211	43789	39877	36456	27932	20714	14366	6255	8728	14334
1997–98	17856	51617	58372	37582	34649	23853	13966	5936	9156	18197
1998–99	21259	44065	43976	31651	32803	30000	16689	5470	10988	19062
1999–00	24972	41750	47015	47657	38333	27768	17850	5563	12694	21601
2000–01	26775	48595	54449	45160	33957	22632	16085	4390	11686	14532
2001–02	16031	39017	47535	33092	23114	28170	17698	2674	7114	16819
2002–03	21537	39785	48800	35693	23301	23265	23176	4317	6895	11942
2003–04	29766	40117	41628	43117	35867	26413	18488	3013	7497	20858
2004–05	20276	39198	39509	29593	27857	25968	17242	3142	5284	21036
2005–06	18277	33423	44773	36937	27017	9503	6998	1980	6193	16261
2006–07	14926	31615	31949	31978	25073	19145	10946	0	0	21493
2007–08	17194	26431	32201	23107	22521	13704	8229	0	0	9548
2008–09	8164	20547	23438	15963	14112	8769	6343	1543	3038	8696
2009–10	11031	19649	18278	15795	14635	10413	9732	4564	6252	10115
2010–11	11000	21682	26461	17303	19976	14958	6476	2147	9027	18573
2011–12	12360	22648	18382	17894	17765	9866	3381	1144	8681	15873
Warrnambool Region										
1978–79	8104	22165	25839	21375	21303	13049	6593	3415	2103	11602
1979–80	11991	16613	26181	22332	19228	10772	5131	2607	3619	6892
1980–81	15185	21081	19695	16369	14903	9807	5578	1174	1722	6309
1981–82	10046	16415	22728	18670	18287	10528	3716	2983	2033	6094
1982–83	10564	18176	12905	16359	10668	8362	4668	1255	1789	6690
1983–84	10005	21575	26259	23565	14651	8337	7648	2370	1057	6962
1984–85	9336	11312	27096	22678	17909	10043	5467	1313	1826	6687
1985–86	10476	10283	13952	17371	13820	5005	4152	1773	1324	6564
1986–87	6570	8007	13709	14513	13661	10126	4422	2718	3054	8274
1987–88	4379	11467	21930	16551	15535	8938	5147	1026	2183	3044
1988–89	2949	11417	11431	11996	10148	7288	4288	2115	2559	3494
1989–90	3326	9418	13232	9896	12036	5403	3212	1475	1784	3124
1990–91	2698	10403	14479	8969	8625	7445	5662	2515	4447	2932
1991–92	3921	10709	18700	13469	15811	11717	8486	3881	3122	3566
1992–93	3739	10154	23889	15113	20092	11484	7822	3275	6100	6239
1993–94	3497	9801	14095	19555	24638	10836	5295	3659	3980	4488
1994–95	4133	13782	21853	13924	8864	6431	7315	4192	2557	4421
1995–96	3593	8827	21064	15096	10796	5143	7550	2996	3955	3568
1996–97	3543	13998	17090	16894	12827	7158	4714	3099	4538	3479
1997–98	5400	11397	15801	11149	11343	9349	7297	4229	4688	7438
1998–99	8261	23501	29368	28450	26652	17398	9830	3924	4694	8049
1999–00	7645	18036	21438	22715	19748	14563	5754	2746	6295	10102
2000–01	10702	16690	29745	27621	15918	10020	10520	2686	6500	5194
2001–02	6015	14906	23313	20375	18990	9906	6040	1018	1876	7166
2002–03	7915	18776	22740	18436	11462	8710	4453	761	2682	5541
2003–04	5729	10220	16028	18234	14967	11498	7533	2501	3840	9294
2004–05	6073	13443	21616	17938	14019	13332	6106	5447	3024	8221
2005–06	6489	11966	26435	21826	15382	6177	4098	1782	2581	7863
2006–07	5700	12510	14690	18362	13408	10515	1873	0	0	9307
2007–08	7820	13691	16473	14167	12355	8072	3946	0	0	3610
2008–09	4892	13799	16570	16482	10314	4845	3278	1414	991	2509
2009–10	3081	11171	15517	12977	10537	5970	4859	1669	1962	3903
2010–11	3314	7707	16817	9529	5078	5138	1877	738	2773	7474
2011–12	3184	12720	13836	11768	3080	991	419	431	3301	8128

Data source: Fisheries Victoria CandE Database (11 January 2013)

Table 8.2.2 Monthly catch mass during fishing years from 1978–79 to 2011–12 for each region

Data: non-screened and non-selected.

Fishing year	Catch (kg) for each month									
	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug–Sep
Apollo Bay Region										
1978–79	22820	28224	19599	16888	12339	4653	2566	1297	252	5681
1979–80	25980	20386	20098	19745	7207	8213	4126	680	1004	3572
1980–81	18208	20788	24673	16090	11718	7449	3330	580	858	8751
1981–82	27691	29403	25404	16924	7996	3910	1598	1323	842	7561
1982–83	26762	37334	16099	12361	6794	6016	3096	899	978	4453
1983–84	18866	25443	14922	15403	7924	4349	4399	455	1150	4985
1984–85	13871	18298	22591	22208	11166	5324	4383	1968	690	4818
1985–86	19097	18750	14708	11647	10982	2458	3014	671	742	7200
1986–87	11248	13932	13046	14252	16017	9307	2564	1083	584	3690
1987–88	4752	14731	14018	12237	11660	5393	4079	1156	1099	3565
1988–89	5816	12395	15154	12169	10705	7508	3741	2070	1735	3269
1989–90	7174	16152	15716	11625	11533	4281	1924	1626	1438	3984
1990–91	5390	12865	12855	11962	7625	4084	3968	1266	1832	1742
1991–92	6370	11632	9844	12674	10941	6631	4438	1393	1305	3540
1992–93	6496	15129	17908	9153	13170	10734	4008	1165	2645	4858
1993–94	12404	20586	14927	21449	21155	8128	4340	3463	3023	4361
1994–95	9966	20952	19003	16107	13564	6451	5293	2549	1651	3082
1995–96	5314	14057	14506	14342	10888	3981	5173	2266	2309	4802
1996–97	4395	15321	14122	15511	11208	9794	5305	1783	3050	4533
1997–98	9433	25889	20156	12900	15824	6761	5177	2341	2317	6035
1998–99	7997	16040	16075	16529	16237	9756	4448	1465	3012	8132
1999–00	9991	18386	13470	18121	12302	12106	3706	1650	5070	11779
2000–01	14651	20271	22836	16684	10060	7442	7443	2221	3868	5574
2001–02	11225	18879	19607	12167	11018	8634	5930	289	2359	7154
2002–03	9259	18170	17618	12668	7957	7736	7145	555	1557	6842
2003–04	9079	19789	16640	14925	11416	8624	4651	1131	1735	5996
2004–05	9072	16229	13787	9135	7979	4346	3091	1502	677	3923
2005–06	5625	9357	10808	7914	5411	2271	1449	581	1032	7297
2006–07	5451	13022	10931	11140	7529	6470	2036	0	0	5856
2007–08	7057	11240	9021	8642	9145	4376	2605	0	0	3484
2008–09	4356	9952	10313	6479	7420	4014	3430	873	678	1886
2009–10	4892	9197	8537	7679	5374	3099	2607	903	1143	3321
2010–11	5544	7363	9180	4930	5003	3103	2044	925	2527	5700
2011–12	5282	11684	7318	6736	3435	2234	2036	1041	2240	4650
Queenscliff Region										
1978–79	10070	9058	13559	5572	4315	3121	1370	62	2141	15686
1979–80	9074	9574	9935	10301	3589	2629	1607	198	2046	12278
1980–81	13743	9867	12020	8403	5237	2230	1066	27	1717	12957
1981–82	8766	8765	10909	9174	6288	2484	952	128	1577	11158
1982–83	12306	11485	9672	8691	7749	2699	1476	302	2600	13416
1983–84	10197	12325	15631	15564	8452	4484	1550	554	2212	12676
1984–85	8948	9915	10482	7206	7001	2379	709	165	390	7077
1985–86	8785	8847	7714	6894	3005	1447	437	250	484	7696
1986–87	5810	6072	6594	5698	3806	1809	325	398	1435	7410
1987–88	3898	7254	9680	6510	5653	2054	389	81	1325	2768
1988–89	2822	7050	6577	4407	3406	1780	406	353	2687	5017
1989–90	4024	10125	10928	8283	7226	3684	1246	195	2352	6268
1990–91	4742	8976	9683	6961	4024	1685	372	99	3460	5060
1991–92	4053	7524	6645	8252	5955	2481	666	593	2806	4819
1992–93	3407	6293	7420	4248	3808	2725	1080	316	3298	4014
1993–94	5786	7873	6417	5532	4874	1446	937	339	2558	4648
1994–95	2669	6603	5419	4737	2694	1528	1239	303	2034	3714
1995–96	2175	4493	5351	6231	4840	1859	863	424	3008	3479
1996–97	1499	4216	4339	5083	2465	1553	750	457	2246	4532
1997–98	3156	4667	5768	3766	2756	899	381	364	2546	4125
1998–99	2268	5358	4653	4468	3092	2505	849	564	3275	6095
1999–00	3708	6924	7735	7921	4298	2293	399	480	2940	7668
2000–01	6042	8616	6517	4754	2546	1543	1018	539	4759	6679
2001–02	3539	6635	6644	3524	2540	1901	376	242	2728	5214
2002–03	2887	5987	5490	4438	2588	3070	1424	261	2650	5473
2003–04	3129	8037	6105	4814	2823	1491	1477	469	2003	8214
2004–05	4139	6998	8338	3618	2936	2210	1118	420	2020	5456
2005–06	2245	6182	5129	3999	1593	375	557	241	1375	5833
2006–07	2186	4683	5048	4912	3007	1743	1421	190	1826	5506
2007–08	2891	5631	3610	2220	2448	1020	597	180	1594	3385
2008–09	1500	3951	4580	1629	2795	1179	365	145	2260	2793
2009–10	2079	4129	4040	2497	1787	1230	993	342	4061	10371
2010–11	3291	6366	5260	2825	1682	1214	1491	642	3178	9359
2011–12	3658	7786	6907	1821	732	1176	1660	897	4002	6710

Data source: Fisheries Victoria CandE Database (11 January 2013)

Table 8.2.3 Monthly catch mass during fishing years from 1978–79 to 2011–12 for each region

Data: non-screened and non-selected.

Fishing year	Catch (kg) for each month									
	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug–Sep
San Remo Region										
1978–79	4235	6033	7924	5465	6435	3649	2380	818	1109	4453
1979–80	4683	5597	5650	6880	4771	3823	989	176	1155	3016
1980–81	4309	7669	8585	8230	5463	3713	2861	762	1968	3699
1981–82	3514	9732	10220	8730	6908	2802	1033	805	2583	6336
1982–83	5986	10088	8851	10982	6368	4939	2201	1523	2819	7118
1983–84	4731	6788	5810	5491	4826	3630	2242	508	1644	5466
1984–85	3655	7483	6917	5983	5275	3800	1442	400	1620	3492
1985–86	3797	4712	6521	3567	4630	2424	1885	304	962	2102
1986–87	3255	4371	4188	4510	3963	1552	780	441	1279	2420
1987–88	2357	4960	3357	2225	1797	1090	657	501	972	732
1988–89	1042	2359	3457	2686	1946	1446	494	206	850	1123
1989–90	1984	3630	3500	2638	2659	1146	361	426	997	1171
1990–91	626	1918	2606	1965	2404	1706	1418	606	1602	2289
1991–92	1093	1727	1567	2078	2291	1633	1198	392	907	1972
1992–93	1037	3113	3998	2855	4042	2793	1183	835	2541	2777
1993–94	2003	4709	5361	5894	4745	1906	680	1411	2152	2049
1994–95	1412	5011	5608	3838	3241	2670	1630	809	2422	1718
1995–96	1115	2903	3548	2334	2333	1044	969	1035	1550	1060
1996–97	619	2711	2952	2539	2672	1722	1893	1459	2197	1551
1997–98	1688	3605	4258	2680	3382	2655	2086	1296	2023	2591
1998–99	1215	3594	4418	2884	2037	2019	1440	1209	2254	3243
1999–00	1646	2758	3454	3529	2542	2058	897	1339	2192	2366
2000–01	1672	2745	3321	2438	1865	1490	778	1338	2464	1903
2001–02	1055	2738	2949	1794	1869	1161	801	182	1442	2290
2002–03	704	2264	1769	1804	1213	1526	686	240	1206	1795
2003–04	890	1762	1806	1086	2621	1001	827	350	1091	2435
2004–05	837	745	861	1310	1987	1058	802	984	704	4132
2005–06	1741	3059	4765	2901	3371	579	522	836	1629	3186
2006–07	1417	3910	2680	2997	2849	1411	520	826	1390	2845
2007–08	1265	2961	3192	2808	2482	1282	761	386	2642	2769
2008–09	696	2294	2706	2184	2323	1654	1407	837	1012	1875
2009–10	953	3390	3506	3357	2517	1205	1040	1259	2278	2810
2010–11	1601	4776	5883	2604	1594	1644	1533	413	2692	5005
2011–12	1531	4670	5060	2633	1777	1699	1085	189	3234	2885
Lakes Entrance Region										
1978–79	10750	6308	5602	3605	1893	1127	0	0	72	2259
1979–80	2427	4992	3863	2104	816	1198	730	0	559	893
1980–81	5416	5099	4210	2913	563	641	30	0	0	22
1981–82	4519	6641	2276	3280	471	680	0	0	42	114
1982–83	5537	4182	1474	693	0	0	0	15	0	0
1983–84	3048	5326	2384	525	18	305	75	0	0	0
1984–85	7945	4775	2715	1823	640	675	0	0	14	0
1985–86	7287	5942	2790	710	90	436	73	0	441	445
1986–87	3901	3984	1602	982	443	0	0	0	145	569
1987–88	1678	4394	3268	884	734	0	224	86	64	394
1988–89	2678	4060	3370	959	1220	940	0	0	100	142
1989–90	3377	2863	1542	863	664	367	5	12	332	524
1990–91	2027	3289	1948	1430	602	31	0	0	0	0
1991–92	1782	2687	1279	132	33	0	0	0	0	0
1992–93	612	2169	2333	1197	797	364	132	0	0	0
1993–94	1234	2180	2418	734	367	352	47	8	14	44
1994–95	1637	3247	2695	2096	997	1343	431	110	30	123
1995–96	585	1524	1649	900	491	445	80	185	58	195
1996–97	1019	2907	2419	1872	1878	682	211	524	455	369
1997–98	3026	5153	1026	1097	596	361	31	78	164	90
1998–99	973	2762	2834	1945	653	360	269	12	21	0
1999–00	1219	2341	824	1086	654	552	332	69	147	264
2000–01	1904	3239	1862	1080	361	542	630	7	0	0
2001–02	172	1005	1071	169	864	101	94	30	0	327
2002–03	1239	1690	1311	527	179	1	0	0	0	2
2003–04	459	1311	661	233	6	0	0	67	67	309
2004–05	511	1329	1139	292	541	239	37	5	0	2
2005–06	49	1051	373	240	418	16	12	0	0	0
2006–07	294	855	577	414	336	9	0	0	0	0
2007–08	462	1091	30	121	126	13	0	0	0	0
2008–09	61	768	227	69	129	19	0	0	16	0
2009–10	336	598	304	76	0	0	28	0	0	0
2010–11	193	439	875	352	304	452	0	0	0	0
2011–12	482	774	159	25	50	26	0	0	0	6

Data source: Fisheries Victoria CandE Database (11 January 2013)

Table 9.1.1. Monthly catch numbers during fishing years from 1978–79 to 2011–12 for each zone

Data: non-screened and non-selected.

Fishing year	Catch (number) for each month									
	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug–Sep
Western Zone										
1978–79	64678	92733	94402	66547	70751	34549	12951	5653	6515	36171
1979–80	73575	62992	78984	71451	53892	33819	12075	5662	9616	41595
1980–81	91275	103349	106090	94489	61668	32845	11911	3744	7465	35633
1981–82	80606	90249	99606	73132	65833	31059	9360	5568	8590	35093
1982–83	73053	89766	69386	73841	53689	35624	13882	2700	8560	34530
1983–84	60090	85971	81181	71615	45321	22733	13723	2876	5722	24512
1984–85	52792	59756	81889	71481	53202	29553	12601	3506	4933	24248
1985–86	66197	58576	57777	49388	46947	18476	9998	3087	5199	30237
1986–87	56426	60152	58512	52973	50126	32540	8917	4518	7577	21339
1987–88	25559	71856	73451	57150	55436	28905	12137	3999	6114	14243
1988–89	22335	60798	56186	50766	50507	36048	13524	5569	10073	16690
1989–90	29674	64910	72911	54116	60973	28742	11967	4859	9298	17181
1990–91	21985	55034	63640	53639	51064	31530	20789	6344	16459	16305
1991–92	33055	69995	78279	72633	69591	46528	29353	9662	12186	17987
1992–93	26685	66188	93464	57461	67201	49250	25452	7867	17012	22591
1993–94	42145	75414	67448	79618	83273	38667	20275	12494	15845	21284
1994–95	34226	87951	91193	68963	53383	32005	29395	11543	13496	21960
1995–96	34590	73872	86476	77732	67502	30987	28791	8631	14056	19326
1996–97	30074	80091	73741	70105	51589	36998	22743	10413	15658	22453
1997–98	38463	95737	100910	65065	63251	41221	26633	12164	16040	32959
1998–99	45558	94894	96584	83099	81874	62475	32452	11602	20507	38610
1999–00	52889	91115	93682	99918	78188	60256	30385	11275	26494	48287
2000–01	63042	99995	122087	101717	68565	44611	36537	9848	23835	27672
2001–02	41633	87013	103986	77680	61302	54858	32671	4180	12392	34507
2002–03	48861	90599	101161	76395	49690	44965	38370	5975	12333	26214
2003–04	46929	85737	83892	87395	69970	50880	32132	6520	13338	38219
2004–05	44047	79920	83208	62429	54511	44772	27711	9647	9573	35271
2005–06	39286	65144	92533	75294	51952	18828	12844	4195	10583	34774
2006–07	33966	69546	66556	71507	52520	39847	16478	0	0	41121
2007–08	41716	62768	68229	53623	49359	28395	15586	0	0	18318
2008–09	22706	52712	57896	44249	34641	19138	13158	3604	5062	14495
2009–10	24457	47539	49184	41431	34886	21720	18848	7479	10985	20042
2010–11	26220	45416	62481	38595	36300	27481	11934	4457	16782	37647
2011–12	27444	58142	47324	44341	28862	15557	6605	2916	16071	31799
Eastern Zone										
1978–79	22546	19019	23011	12759	11139	6744	2849	600	2902	21232
1979–80	15698	18317	17827	18391	9265	6233	2702	276	3524	16203
1980–81	22943	20316	22757	17454	9901	5635	2900	433	3194	17220
1981–82	17390	22905	21476	19515	12148	5341	1769	700	3162	15758
1982–83	23424	23238	18906	19081	12731	6456	2711	1334	4650	19190
1983–84	18192	22468	22304	21245	12452	7454	3176	661	3501	16698
1984–85	19302	18644	17066	13015	10859	5352	1464	359	1284	8852
1985–86	18237	16631	14229	9319	6152	3279	1795	433	1424	9171
1986–87	11537	12532	10241	9241	6846	2910	757	501	2276	9320
1987–88	7738	14176	14116	8649	7558	2670	952	543	1926	3821
1988–89	6409	12795	12529	7750	6040	3494	772	393	3602	6310
1989–90	9726	16606	15955	12261	10721	5494	1588	499	3536	8153
1990–91	7670	13952	13529	10548	7084	3170	1687	549	5479	8065
1991–92	7221	11654	9729	10678	8064	3853	1705	823	3406	6439
1992–93	5270	11268	13240	8032	7624	4916	2036	762	4599	5591
1993–94	9062	13422	12272	10233	8175	2804	1242	1022	3507	5963
1994–95	5074	12489	11132	8452	5563	4213	2163	803	3488	4824
1995–96	3795	7729	9026	7952	6386	2687	1370	1209	3473	4094
1996–97	2869	8314	7632	7627	5386	2976	2062	1734	3839	5355
1997–98	6847	10529	9298	6402	5249	2833	1797	1098	3972	6010
1998–99	3957	9695	9912	8307	5226	4108	1998	1191	4739	8904
1999–00	6346	11848	12266	12525	6910	4081	1185	1440	4329	10196
2000–01	9927	14068	10752	7667	4245	3024	2182	1414	6208	7495
2001–02	4877	9659	10281	5544	4690	2971	978	330	3336	7024
2002–03	4895	8961	7756	6205	3735	4255	1662	328	3160	6935
2003–04	4956	10859	7679	6097	4659	2024	1820	525	2543	9664
2004–05	5898	8162	9907	4739	4630	2872	1340	767	2016	8178
2005–06	4131	9321	9002	6330	4192	763	850	676	2352	8267
2006–07	4103	8900	7491	7593	5194	2787	1528	605	2364	7057
2007–08	4833	8786	5769	4167	4034	1961	1082	338	2833	4947
2008–09	2354	5857	6313	2970	4100	2217	1144	577	2435	3746
2009–10	3192	6786	6737	4964	3541	1971	1537	1055	5741	14207
2010–11	5873	10598	11097	5983	3389	3076	2272	882	5121	14197
2011–12	6139	12355	10331	3986	2303	2546	2317	769	5262	8750

Data source: Fisheries Victoria CandE Database (11 January 2013)

Table 9.2.1. Monthly catch numbers during fishing years from 1978–79 to 2011–12 for each region

Data: non-screened and non-selected.

Fishing year	Catch (number) for each month									
	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug–Sep
Portland Region										
1978–79	30389	42819	50054	29991	38326	18942	4779	1690	4540	20776
1979–80	33414	26376	35185	32986	30232	16742	3005	2859	5541	31953
1980–81	55099	61594	62348	62073	36064	16270	3773	2018	4852	20814
1981–82	38990	44968	52190	38836	39743	17221	3826	1736	5917	22269
1982–83	32424	35244	41411	45379	35741	21378	6685	744	5973	25512
1983–84	29192	41900	42634	35183	23546	10145	2438	378	3715	13978
1984–85	27526	30337	36633	33035	26705	14564	3065	575	2648	13734
1985–86	33279	30236	30388	23159	24926	11331	3475	742	3273	17742
1986–87	37398	37707	32017	25217	23024	15085	2218	819	4261	10619
1987–88	15264	44554	37677	30259	29171	14856	3687	1899	2964	7497
1988–89	12469	35024	30712	26895	30377	21765	6085	1544	5576	10001
1989–90	17837	37863	42539	32151	37497	19332	7146	2055	6222	10113
1990–91	12625	30404	35599	32525	34522	19950	11302	2639	9952	11188
1991–92	21261	45232	48806	45756	42236	28752	17200	4567	7868	10996
1992–93	14823	39209	51341	32723	33943	27689	14599	3496	7805	11000
1993–94	24993	43620	37831	38493	40395	21492	11063	5863	9198	13137
1994–95	19228	51681	50368	40587	33932	20218	18106	5714	9720	15546
1995–96	24422	50265	51607	49159	46553	21923	17490	4233	8895	12380
1996–97	21231	50219	43368	39099	29895	21709	14591	6425	9169	15024
1997–98	22262	58939	64799	41588	37633	26158	14928	6341	10098	19937
1998–99	26654	52616	49269	37475	38460	34993	18963	6266	12597	20989
1999–00	31828	51011	56446	56180	44409	32568	20860	6477	14697	25169
2000–01	33797	58805	64249	54037	40304	26166	18375	5002	13336	16559
2001–02	20548	47678	55980	39541	28483	34145	20223	2878	8049	19476
2002–03	27686	47819	56528	41324	27833	27087	26330	4716	7852	13465
2003–04	27875	48943	47776	50658	41316	29590	20149	3102	7889	21491
2004–05	25495	46243	44599	33505	32051	27143	18904	3210	5791	22328
2005–06	23942	40650	51959	43087	30946	10755	7656	2064	7007	19026
2006–07	20069	40384	38888	38892	30153	22549	12620	0	0	25102
2007–08	23124	33944	39933	28201	26387	16013	9412	0	0	10673
2008–09	11175	26073	28754	19055	16333	10243	7069	1570	3428	9923
2009–10	14923	24247	22270	19140	17593	12409	11435	4773	7569	11826
2010–11	15144	27798	32827	21494	24845	18263	7678	2637	10975	22189
2011–12	16739	28947	22720	22468	21488	11867	3878	1313	9991	17647
Warrnambool Region										
1978–79	9518	21521	25505	20371	20777	11955	5844	2878	1763	10163
1979–80	12906	16968	25017	20114	17242	9587	4948	2216	3249	6094
1980–81	16202	21484	19331	17016	14708	9295	5208	1208	1770	6088
1981–82	10936	16825	22832	17780	17270	9944	3706	2678	1874	5699
1982–83	11966	17103	12213	15502	10471	7912	4369	1160	1627	4955
1983–84	10938	18965	24023	20856	14016	8237	7266	2108	964	6218
1984–85	10132	11389	24406	19121	15725	9753	5373	1233	1655	6035
1985–86	12208	10450	13526	14836	12234	4644	3904	1668	1299	5785
1986–87	7399	8011	12981	14060	12805	9076	4082	2630	2781	7003
1987–88	4687	11573	21112	15286	15088	8457	4570	1023	2172	3195
1988–89	3547	12363	10963	11928	10118	7198	4207	2019	2599	3468
1989–90	3930	10380	14040	10188	11812	5438	2997	1374	1651	3054
1990–91	3104	11659	15108	9022	8721	7229	5375	2422	4514	3182
1991–92	4807	12274	19112	13547	15641	11161	7894	3676	3144	3649
1992–93	4645	10756	23890	15149	19642	11066	6998	3196	6386	6441
1993–94	4306	10684	15012	19548	23264	9939	5119	3483	3759	3997
1994–95	4790	15210	22032	13539	8130	6025	6198	3519	2261	3608
1995–96	4202	9376	20768	14382	10435	4916	6358	2463	3296	3202
1996–97	4103	14753	17103	16234	11582	6740	4141	2519	3709	3181
1997–98	6646	12656	16037	10825	10958	8917	6608	3636	3809	7219
1998–99	9963	25479	31512	28683	26959	17419	9221	3896	4965	8212
1999–00	9311	20838	22982	24131	20879	15027	5871	2949	6508	10690
2000–01	12575	18157	33306	30193	17036	10620	10820	2790	6737	5409
2001–02	7791	17886	26988	24002	20553	10999	6297	1003	1986	7710
2002–03	10304	21995	25182	20686	12736	9389	4784	737	2894	5630
2003–04	7696	13114	17867	20021	16070	12023	7404	2362	3547	9914
2004–05	7918	15341	23112	19223	14132	12943	5774	5022	3055	8597
2005–06	8542	14148	29026	23444	15196	6025	3756	1587	2551	8278
2006–07	7251	14621	16268	20503	14063	10397	1790	0	0	9701
2007–08	10014	16153	18491	16132	13119	7869	3799	0	0	3970
2008–09	6353	15883	18496	18127	10780	4940	3186	1262	965	2634
2009–10	3832	13312	17569	14036	11396	6119	4750	1774	2230	4525
2010–11	4384	9285	18935	10927	5674	5562	1974	814	3056	8843
2011–12	4125	15278	15841	13355	3496	1127	475	447	3712	9226

Data source: Fisheries Victoria CandE Database (11 January 2013)

Table 9.2.2. Monthly catch numbers during fishing years from 1978–79 to 2011–12 for each region

Data: non-screened and non-selected.

Fishing year	Catch (number) for each month									
	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug–Sep
Apollo Bay Region										
1978–79	24771	28393	18843	16185	11648	3652	2328	1085	212	5232
1979–80	27255	19648	18782	18351	6418	7490	4122	587	826	3548
1980–81	19974	20271	24411	15400	10896	7280	2930	518	843	8731
1981–82	30680	28456	24584	16516	8820	3894	1828	1154	799	7125
1982–83	28663	37419	15762	12960	7477	6334	2828	796	960	4063
1983–84	19960	25106	14524	15576	7759	4351	4019	390	1043	4316
1984–85	15134	18030	20850	19325	10772	5236	4163	1698	630	4479
1985–86	20710	17890	13863	11393	9787	2501	2619	677	627	6710
1986–87	11629	14434	13514	13696	14297	8379	2617	1069	535	3717
1987–88	5608	15729	14662	11605	11177	5592	3880	1077	978	3551
1988–89	6319	13411	14511	11943	10012	7085	3232	2006	1898	3221
1989–90	7907	16667	16332	11777	11664	3972	1824	1430	1425	4014
1990–91	6256	12971	12933	12092	7821	4351	4112	1283	1993	1935
1991–92	6987	12489	10361	13330	11714	6615	4259	1419	1174	3342
1992–93	7217	16223	18233	9589	13616	10495	3855	1175	2821	5150
1993–94	12846	21110	14605	21577	19614	7236	4093	3148	2888	4150
1994–95	10208	21060	18793	14837	11321	5762	5091	2310	1515	2806
1995–96	5966	14231	14101	14191	10514	4148	4943	1935	1865	3744
1996–97	4740	15119	13270	14772	10112	8549	4011	1469	2780	4248
1997–98	9555	24142	20074	12652	14660	6146	5097	2187	2133	5803
1998–99	8941	16799	15803	16941	16455	10063	4268	1440	2945	9409
1999–00	11750	19267	14254	19608	12900	12661	3654	1849	5289	12428
2000–01	16670	23033	24533	17486	11225	7825	7342	2056	3762	5704
2001–02	13294	21449	21018	14137	12266	9714	6151	299	2357	7321
2002–03	10871	20785	19451	14385	9121	8489	7256	522	1587	7119
2003–04	11358	23680	18249	16716	12584	9267	4580	1056	1902	6814
2004–05	10634	18336	15497	9701	8328	4686	3033	1415	727	4346
2005–06	6802	10346	11548	8763	5810	2048	1432	544	1025	7470
2006–07	6646	14541	11400	12112	8304	6901	2068	0	0	6318
2007–08	8578	12671	9805	9290	9853	4513	2375	0	0	3675
2008–09	5178	10756	10646	7067	7528	3955	2903	772	669	1938
2009–10	5702	9980	9345	8255	5897	3192	2663	932	1186	3691
2010–11	6692	8333	10719	6174	5781	3656	2282	1006	2751	6615
2011–12	6580	13917	8763	8518	3878	2563	2252	1156	2368	4926
Queenscliff Region										
1978–79	9458	8991	12740	5709	4445	2958	1302	45	2179	15864
1979–80	9283	9261	10038	11430	3735	2747	1397	164	2334	13453
1980–81	13967	9700	12164	8870	5295	2236	922	21	1985	14150
1981–82	10334	9677	11895	9483	6213	2357	1060	123	1571	11333
1982–83	13339	11509	9981	9336	7652	2599	1099	238	2771	13640
1983–84	11173	12459	15752	16039	8615	4391	1510	337	2240	12869
1984–85	8937	8949	9309	6606	6114	1954	598	108	386	6535
1985–86	9008	7900	6948	6098	2684	1214	300	221	430	7511
1986–87	5840	5979	5813	5132	3416	1563	238	305	1254	7172
1987–88	4300	7198	8744	5733	5227	1785	279	76	1219	2845
1988–89	3162	6971	6762	4467	3262	1667	383	279	2924	5370
1989–90	4791	10406	11289	9122	7851	3974	1260	195	2532	6788
1990–91	5330	9304	9748	7420	4392	1694	413	108	3982	6068
1991–92	4798	8060	7237	8726	6075	2410	652	494	2755	5096
1992–93	3842	6910	7874	4632	3979	2415	1053	235	2888	3709
1993–94	6505	7559	6063	5292	4383	1219	738	233	2227	4671
1994–95	2602	5882	4935	4125	2353	1391	942	206	1982	3651
1995–96	2332	4165	4885	5379	4185	1446	616	357	2507	3240
1996–97	1490	3850	3426	4133	2120	1290	658	451	2167	4123
1997–98	3073	3891	5351	3545	2438	773	388	269	2506	4078
1998–99	2179	4880	4315	4473	3116	2310	724	455	3306	6556
1999–00	3881	7587	8599	8846	4474	2211	364	465	2886	8417
2000–01	6813	9153	6693	4937	2620	1555	983	533	4538	6218
2001–02	3827	6618	7034	3865	2709	2083	345	202	2461	5294
2002–03	3165	5606	5353	4290	2619	3103	1173	194	2467	5793
2003–04	3744	8376	5881	5028	2857	1339	1300	323	1862	8010
2004–05	4694	6468	8467	3531	2820	1969	797	235	1590	5318
2005–06	2630	6050	4864	3853	1423	345	503	185	1208	6046
2006–07	2622	4852	4938	4835	2922	1710	1084	132	1507	5218
2007–08	3327	5535	3301	1906	2217	1003	516	145	1376	3421
2008–09	1724	3700	4164	1312	2267	1008	237	116	1859	2750
2009–10	2137	3739	3737	2205	1654	1118	900	270	4195	12186
2010–11	4234	6321	5620	3253	1902	1359	1206	579	3393	10834
2011–12	4334	7900	6861	1947	757	1267	1606	628	3455	6985

Data source: Fisheries Victoria CandE Database (11 January 2013)

Table 9.2.3. Monthly catch numbers during fishing years from 1978–79 to 2011–12 for each region

Data: non-screened and non-selected.

Fishing year	Catch (number) for each month									
	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug–Sep
San Remo Region										
1978–79	3425	4645	5771	4222	4913	2670	1547	555	676	3078
1979–80	4083	4833	4392	5478	4862	2570	705	112	722	2067
1980–81	4014	6044	6757	6170	4091	2927	1955	412	1209	3031
1981–82	3229	7404	7762	6770	5460	2348	709	577	1551	4315
1982–83	5242	8307	7632	9161	5079	3865	1612	1084	1879	5550
1983–84	4259	5901	4885	4865	3825	2855	1606	324	1261	3829
1984–85	3375	5827	5735	4919	4212	2707	866	251	888	2317
1985–86	3123	3835	5344	2653	3396	1715	1455	212	589	1312
1986–87	2617	3634	3194	3398	3047	1347	519	196	936	1739
1987–88	2009	3555	2528	2160	1610	885	459	406	669	548
1988–89	900	2116	3043	2424	1640	1148	389	114	595	790
1989–90	1640	3368	3126	2365	2320	1185	324	296	789	901
1990–91	594	1855	2291	1733	2073	1447	1274	441	1497	1997
1991–92	920	1486	1571	1840	1963	1443	1053	329	651	1343
1992–93	937	2771	3631	2455	3084	2167	898	527	1711	1882
1993–94	1551	3763	4049	4308	3495	1309	466	786	1274	1254
1994–95	1037	3785	4057	2759	2467	1894	945	514	1477	1063
1995–96	917	2250	2719	1778	1680	712	682	685	915	669
1996–97	483	1971	2181	1774	1874	1146	1214	839	1285	936
1997–98	1324	2575	3074	1929	2323	1758	1387	759	1335	1860
1998–99	938	2622	3444	2434	1532	1477	1033	724	1416	2348
1999–00	1363	2226	2942	2726	1868	1443	576	912	1318	1580
2000–01	1405	2173	2543	1830	1284	976	517	874	1670	1277
2001–02	866	2113	2242	1514	1323	800	548	102	875	1460
2002–03	649	1890	1395	1489	969	1151	489	134	693	1141
2003–04	869	1360	1294	873	1799	685	520	160	638	1445
2004–05	687	570	564	1004	1358	723	515	529	426	2858
2005–06	1463	2416	3813	2314	2457	403	340	491	1144	2221
2006–07	1193	3236	2146	2387	2035	1066	444	473	857	1839
2007–08	1109	2423	2437	2186	1740	950	566	193	1457	1526
2008–09	586	1702	2013	1615	1759	1200	907	461	570	996
2009–10	777	2633	2809	2705	1887	853	622	785	1546	2021
2010–11	1496	3999	4876	2473	1324	1493	1066	303	1728	3363
2011–12	1391	3899	3365	2022	1510	1263	711	141	1807	1762
Lakes Entrance Region										
1978–79	9663	5383	4500	2828	1781	1116	0	0	47	2290
1979–80	2332	4223	3397	1483	668	916	600	0	468	683
1980–81	4962	4572	3836	2414	523	472	23	0	0	39
1981–82	3827	5833	1819	3262	475	636	0	0	40	110
1982–83	4843	3422	1293	584	0	0	0	12	0	0
1983–84	2760	4108	1667	341	12	208	60	0	0	0
1984–85	6990	3868	2022	1490	533	691	0	0	10	0
1985–86	6106	4896	1937	568	72	350	40	0	405	348
1986–87	3080	2919	1234	711	383	0	0	0	86	409
1987–88	1429	3423	2844	756	721	0	214	61	38	428
1988–89	2347	3708	2724	859	1138	679	0	0	83	150
1989–90	3295	2832	1540	774	550	335	4	8	215	464
1990–91	1746	2793	1490	1395	619	29	0	0	0	0
1991–92	1503	2108	921	112	26	0	0	0	0	0
1992–93	491	1587	1735	945	561	334	85	0	0	0
1993–94	1006	2100	2160	633	297	276	38	3	6	38
1994–95	1435	2822	2140	1568	743	928	276	83	29	110
1995–96	546	1314	1422	795	521	529	72	167	51	185
1996–97	896	2493	2025	1720	1392	540	190	444	387	296
1997–98	2450	4063	873	928	488	302	22	69	131	72
1998–99	840	2193	2153	1400	578	321	241	12	17	0
1999–00	1102	2035	725	953	568	427	245	63	125	199
2000–01	1709	2742	1516	900	341	493	682	7	0	0
2001–02	184	928	1005	165	658	88	85	26	0	270
2002–03	1081	1465	1008	426	147	1	0	0	0	1
2003–04	343	1123	504	196	3	0	0	42	43	209
2004–05	517	1124	876	204	452	180	28	3	0	2
2005–06	38	855	325	163	312	15	7	0	0	0
2006–07	288	812	407	371	237	11	0	0	0	0
2007–08	397	828	31	75	77	8	0	0	0	0
2008–09	44	455	136	43	74	9	0	0	6	0
2009–10	278	414	191	54	0	0	15	0	0	0
2010–11	143	278	601	257	163	224	0	0	0	0
2011–12	414	556	105	17	36	16	0	0	0	3

Data source: Fisheries Victoria CandE Database (11 January 2013)

Table 10.1.1. Monthly mean mass per SRL during fishing years from 1978–79 to 2011–12 for each zone

Data: non-screened and non-selected; SRL, southern rock lobster.

Fishing year	Mean mass per SRL (kg) for each month									
	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug–Sep
Western Zone										
1978–79	0.856	0.980	0.994	1.026	1.016	1.082	1.109	1.164	1.094	1.101
1979–80	0.887	0.999	1.065	1.065	1.070	1.058	0.991	1.033	1.088	1.022
1980–81	0.881	0.988	1.020	1.003	1.040	1.075	1.149	1.163	1.086	1.059
1981–82	0.885	0.965	1.022	1.054	1.001	1.030	0.947	1.108	1.099	1.110
1982–83	0.902	1.011	1.026	1.010	1.020	1.071	1.085	1.050	1.041	1.112
1983–84	0.908	1.006	1.039	1.048	1.014	1.032	1.068	1.108	1.026	1.097
1984–85	0.893	0.984	1.045	1.089	1.058	1.042	1.055	1.095	1.096	1.105
1985–86	0.866	0.955	0.998	1.065	1.041	1.076	1.137	1.098	1.071	1.071
1986–87	0.890	0.947	1.001	1.017	1.052	1.066	1.052	1.008	1.016	1.058
1987–88	0.915	0.945	0.990	1.004	1.007	1.034	1.103	1.018	1.085	0.990
1988–89	0.916	0.912	0.990	0.976	0.960	0.802	1.022	1.018	0.962	0.965
1989–90	0.853	0.893	0.928	0.948	0.949	0.964	1.004	1.103	1.004	0.984
1990–91	0.851	0.915	0.947	0.956	0.944	0.981	0.965	0.985	0.949	0.915
1991–92	0.833	0.883	0.923	0.938	0.941	0.969	1.006	1.010	0.950	0.958
1992–93	0.831	0.912	0.936	0.941	0.951	0.968	1.021	1.005	0.964	0.970
1993–94	0.864	0.918	0.961	0.995	1.028	1.042	1.036	1.067	1.033	1.032
1994–95	0.876	0.934	0.965	0.999	1.031	0.997	1.019	1.115	1.035	1.018
1995–96	0.832	0.914	0.964	0.956	0.961	0.961	1.019	1.103	1.062	1.048
1996–97	0.836	0.913	0.964	0.982	1.007	1.018	1.072	1.070	1.042	0.995
1997–98	0.850	0.929	0.935	0.947	0.977	0.969	0.993	1.028	1.008	0.961
1998–99	0.823	0.881	0.926	0.922	0.924	0.915	0.954	0.936	0.912	0.913
1999–00	0.806	0.858	0.874	0.886	0.900	0.903	0.899	0.883	0.908	0.900
2000–01	0.827	0.856	0.877	0.880	0.874	0.899	0.932	0.944	0.925	0.914
2001–02	0.799	0.837	0.870	0.845	0.867	0.851	0.908	0.952	0.916	0.902
2002–03	0.792	0.847	0.881	0.874	0.860	0.883	0.906	0.943	0.903	0.928
2003–04	0.950	0.818	0.886	0.873	0.890	0.915	0.955	1.019	0.980	0.946
2004–05	0.804	0.862	0.900	0.908	0.915	0.975	0.954	1.046	0.939	0.941
2005–06	0.774	0.840	0.886	0.886	0.920	0.953	0.977	1.035	0.927	0.904
2006–07	0.768	0.822	0.865	0.860	0.876	0.907	0.901	0.861	0.861	0.891
2007–08	0.769	0.818	0.846	0.856	0.892	0.921	0.948	0.870	0.870	0.908
2008–09	0.767	0.840	0.869	0.880	0.919	0.921	0.992	1.063	0.930	0.903
2009–10	0.777	0.842	0.861	0.880	0.876	0.897	0.912	0.954	0.852	0.865
2010–11	0.757	0.809	0.840	0.823	0.828	0.844	0.871	0.855	0.854	0.843
2011–12	0.759	0.809	0.835	0.821	0.841	0.841	0.884	0.897	0.885	0.901
Eastern Zone										
1978–79	1.111	1.125	1.177	1.148	1.135	1.171	1.316	1.467	1.145	1.055
1979–80	1.031	1.101	1.091	1.049	0.990	1.227	1.231	1.356	1.067	0.999
1980–81	1.023	1.114	1.090	1.120	1.138	1.169	1.365	1.821	1.154	0.969
1981–82	0.966	1.098	1.090	1.086	1.125	1.117	1.122	1.333	1.329	1.117
1982–83	1.017	1.108	1.058	1.067	1.109	1.183	1.356	1.379	1.165	1.070
1983–84	0.988	1.088	1.068	1.016	1.068	1.129	1.218	1.607	1.101	1.087
1984–85	1.065	1.189	1.179	1.154	1.189	1.281	1.469	1.575	1.576	1.194
1985–86	1.089	1.173	1.196	1.199	1.256	1.313	1.334	1.279	1.325	1.117
1986–87	1.124	1.151	1.209	1.211	1.200	1.155	1.459	1.675	1.256	1.116
1987–88	1.025	1.172	1.155	1.112	1.083	1.178	1.334	1.229	1.226	1.019
1988–89	1.021	1.053	1.070	1.039	1.088	1.192	1.165	1.420	1.010	0.996
1989–90	0.965	1.001	1.001	0.961	0.984	0.946	1.015	1.269	1.041	0.977
1990–91	0.964	1.017	1.052	0.982	0.992	1.080	1.061	1.282	0.924	0.911
1991–92	0.959	1.024	0.976	0.980	1.027	1.068	1.093	1.196	1.090	1.055
1992–93	0.959	1.027	1.039	1.033	1.134	1.197	1.176	1.511	1.270	1.215
1993–94	0.996	1.100	1.157	1.188	1.222	1.321	1.339	1.721	1.347	1.130
1994–95	1.127	1.190	1.233	1.262	1.246	1.315	1.526	1.520	1.286	1.152
1995–96	1.021	1.154	1.169	1.190	1.200	1.246	1.396	1.360	1.329	1.156
1996–97	1.093	1.183	1.272	1.245	1.303	1.330	1.384	1.407	1.276	1.205
1997–98	1.149	1.275	1.189	1.178	1.283	1.382	1.390	1.582	1.192	1.132
1998–99	1.126	1.208	1.201	1.119	1.106	1.189	1.280	1.499	1.171	1.049
1999–00	1.036	1.015	0.979	1.001	1.085	1.201	1.373	1.311	1.220	1.010
2000–01	0.969	1.038	1.088	1.079	1.124	1.182	1.112	1.333	1.163	1.145
2001–02	0.977	1.074	1.037	0.990	1.124	1.065	1.299	1.373	1.250	1.115
2002–03	0.987	1.109	1.105	1.091	1.065	1.080	1.270	1.525	1.220	1.048
2003–04	0.903	1.023	1.116	1.006	1.170	1.231	1.266	1.686	1.243	1.134
2004–05	0.930	1.111	1.044	1.101	1.180	1.221	1.460	1.836	1.351	1.173
2005–06	0.977	1.104	1.140	1.128	1.284	1.272	1.284	1.592	1.277	1.091
2006–07	0.950	1.062	1.109	1.096	1.192	1.135	1.270	1.681	1.360	1.183
2007–08	0.955	1.102	1.184	1.236	1.253	1.181	1.256	1.674	1.495	1.244
2008–09	0.959	1.197	1.190	1.307	1.280	1.287	1.549	1.702	1.350	1.246
2009–10	1.055	1.196	1.165	1.195	1.216	1.235	1.341	1.518	1.104	0.928
2010–11	0.866	1.093	1.083	0.966	1.056	1.076	1.331	1.196	1.146	1.012
2011–12	0.924	1.071	1.174	1.124	1.111	1.139	1.185	1.411	1.375	1.097

Data source: Fisheries Victoria CandE Database (11 January 2013)

Table 10.2.1. Monthly mean mass per SRL during fishing years from 1978–79 to 2011–12 for each region

Data: non-screened and non-selected; SRL, southern rock lobster.

Fishing year	Mean mass per SRL (kg) for each month									
	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug–Sep
Portland Region										
1978–79	0.804	0.946	0.966	1.000	0.998	1.039	1.090	1.106	1.052	1.086
1979–80	0.818	0.983	1.076	1.032	1.033	1.003	0.900	0.897	1.055	1.003
1980–81	0.853	0.979	1.024	1.004	1.041	1.110	1.266	1.289	1.139	1.090
1981–82	0.862	0.919	1.029	1.067	0.997	1.019	0.928	1.072	1.110	1.136
1982–83	0.880	0.999	1.018	1.011	1.044	1.112	1.092	0.917	1.028	1.068
1983–84	0.880	0.943	1.013	1.026	0.993	1.062	1.070	0.956	0.986	1.069
1984–85	0.870	0.962	0.980	0.999	1.018	1.059	1.122	0.970	1.091	1.114
1985–86	0.834	0.891	0.954	1.019	0.965	1.096	1.208	1.273	1.069	1.049
1986–87	0.866	0.928	0.994	0.995	1.001	1.011	1.078	0.922	0.953	0.999
1987–88	0.934	0.936	0.977	0.945	0.981	1.048	1.130	0.995	1.131	0.999
1988–89	0.939	0.903	0.945	0.944	0.910	0.648	0.953	0.963	0.967	0.934
1989–90	0.831	0.856	0.911	0.925	0.915	0.932	0.963	1.099	0.982	0.969
1990–91	0.841	0.891	0.924	0.933	0.926	0.972	0.924	0.936	0.939	0.915
1991–92	0.812	0.873	0.896	0.918	0.917	0.930	0.966	0.981	0.909	0.921
1992–93	0.805	0.895	0.889	0.911	0.904	0.919	0.970	0.991	0.981	0.983
1993–94	0.820	0.891	0.947	0.993	0.985	0.993	1.027	1.060	1.018	0.998
1994–95	0.826	0.918	0.936	0.957	0.960	0.941	0.958	1.073	1.005	0.955
1995–96	0.813	0.888	0.926	0.913	0.927	0.942	0.950	1.006	0.974	0.960
1996–97	0.811	0.872	0.919	0.932	0.934	0.954	0.985	0.974	0.952	0.954
1997–98	0.802	0.876	0.901	0.904	0.921	0.912	0.936	0.936	0.907	0.913
1998–99	0.798	0.837	0.893	0.845	0.853	0.857	0.880	0.873	0.872	0.908
1999–00	0.785	0.818	0.833	0.848	0.863	0.853	0.856	0.859	0.864	0.858
2000–01	0.792	0.826	0.847	0.836	0.843	0.865	0.875	0.878	0.876	0.878
2001–02	0.780	0.818	0.849	0.837	0.811	0.825	0.875	0.929	0.884	0.864
2002–03	0.778	0.832	0.863	0.864	0.837	0.859	0.880	0.915	0.878	0.887
2003–04	1.068	0.820	0.871	0.851	0.868	0.893	0.918	0.971	0.950	0.971
2004–05	0.795	0.848	0.886	0.883	0.869	0.957	0.912	0.979	0.912	0.942
2005–06	0.763	0.822	0.862	0.857	0.873	0.884	0.914	0.959	0.884	0.855
2006–07	0.744	0.783	0.822	0.822	0.832	0.849	0.867	0.969	0.877	0.856
2007–08	0.744	0.779	0.806	0.819	0.853	0.856	0.874	0.969	0.877	0.895
2008–09	0.731	0.788	0.815	0.838	0.864	0.856	0.897	0.983	0.886	0.876
2009–10	0.739	0.810	0.821	0.825	0.832	0.839	0.851	0.956	0.826	0.855
2010–11	0.726	0.780	0.806	0.805	0.804	0.819	0.843	0.814	0.823	0.837
2011–12	0.738	0.782	0.809	0.796	0.827	0.831	0.872	0.871	0.869	0.899
Warrnambool Region										
1978–79	0.851	1.030	1.013	1.049	1.025	1.091	1.128	1.187	1.193	1.142
1979–80	0.929	0.979	1.047	1.110	1.115	1.124	1.037	1.176	1.114	1.131
1980–81	0.937	0.981	1.019	0.962	1.013	1.055	1.071	0.972	0.973	1.036
1981–82	0.919	0.976	0.995	1.050	1.059	1.059	1.003	1.114	1.085	1.069
1982–83	0.883	1.063	1.057	1.055	1.019	1.057	1.068	1.082	1.100	1.350
1983–84	0.915	1.138	1.093	1.130	1.045	1.012	1.053	1.124	1.096	1.120
1984–85	0.921	0.993	1.110	1.186	1.139	1.030	1.018	1.065	1.103	1.108
1985–86	0.858	0.984	1.032	1.171	1.130	1.078	1.064	1.063	1.019	1.135
1986–87	0.888	0.999	1.056	1.032	1.067	1.116	1.083	1.033	1.098	1.181
1987–88	0.934	0.991	1.039	1.083	1.030	1.057	1.126	1.003	1.005	0.953
1988–89	0.831	0.924	1.043	1.006	1.003	1.012	1.019	1.047	0.985	1.008
1989–90	0.846	0.907	0.942	0.971	1.019	0.994	1.072	1.073	1.081	1.023
1990–91	0.869	0.892	0.958	0.994	0.989	1.030	1.053	1.039	0.985	0.921
1991–92	0.816	0.872	0.978	0.994	1.011	1.050	1.075	1.056	0.993	0.977
1992–93	0.805	0.944	1.000	0.998	1.023	1.038	1.118	1.025	0.955	0.969
1993–94	0.812	0.917	0.939	1.000	1.059	1.090	1.034	1.050	1.059	1.123
1994–95	0.863	0.906	0.992	1.028	1.090	1.067	1.180	1.191	1.131	1.225
1995–96	0.855	0.941	1.014	1.050	1.035	1.046	1.188	1.216	1.200	1.114
1996–97	0.863	0.949	0.999	1.041	1.108	1.062	1.138	1.230	1.224	1.094
1997–98	0.812	0.901	0.985	1.030	1.035	1.048	1.104	1.163	1.231	1.030
1998–99	0.829	0.922	0.932	0.992	0.989	0.999	1.066	1.007	0.945	0.980
1999–00	0.821	0.866	0.933	0.941	0.946	0.969	0.980	0.931	0.967	0.945
2000–01	0.851	0.919	0.893	0.915	0.934	0.944	0.972	0.963	0.965	0.960
2001–02	0.772	0.833	0.864	0.849	0.924	0.901	0.959	1.015	0.945	0.929
2002–03	0.768	0.854	0.903	0.891	0.900	0.928	0.931	1.033	0.927	0.984
2003–04	0.744	0.779	0.897	0.911	0.931	0.956	1.017	1.059	1.083	0.937
2004–05	0.767	0.876	0.935	0.933	0.992	1.030	1.058	1.085	0.990	0.956
2005–06	0.760	0.846	0.911	0.931	1.012	1.025	1.091	1.123	1.012	0.950
2006–07	0.786	0.856	0.903	0.896	0.953	1.011	1.046	1.067	0.977	0.959
2007–08	0.781	0.848	0.891	0.878	0.942	1.026	1.039	1.067	0.977	0.909
2008–09	0.770	0.869	0.896	0.909	0.957	0.981	1.029	1.120	1.027	0.953
2009–10	0.804	0.839	0.883	0.925	0.925	0.976	1.023	0.941	0.880	0.862
2010–11	0.756	0.830	0.888	0.872	0.895	0.924	0.951	0.907	0.907	0.845
2011–12	0.772	0.833	0.873	0.881	0.881	0.880	0.883	0.964	0.889	0.881

Data source: Fisheries Victoria CandE Database (11 January 2013)

Table 10.2.2. Monthly mean mass per SRL during fishing years from 1978–79 to 2011–12 by region

Data: non-screened and non-selected; SRL, southern rock lobster.

Fishing year	Mean mass per SRL (kg) for each month									
	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug–Sep
Apollo Bay Region										
1978–79	0.921	0.994	1.040	1.043	1.059	1.274	1.102	1.195	1.189	1.086
1979–80	0.953	1.038	1.070	1.076	1.123	1.097	1.001	1.158	1.215	1.007
1980–81	0.912	1.025	1.011	1.045	1.075	1.023	1.136	1.120	1.018	1.002
1981–82	0.903	1.033	1.033	1.025	0.907	1.004	0.874	1.146	1.054	1.061
1982–83	0.934	0.998	1.021	0.954	0.909	0.950	1.095	1.130	1.019	1.096
1983–84	0.945	1.013	1.027	0.989	1.021	1.000	1.095	1.167	1.103	1.155
1984–85	0.917	1.015	1.084	1.149	1.037	1.017	1.053	1.159	1.096	1.076
1985–86	0.922	1.048	1.061	1.022	1.122	0.983	1.151	0.991	1.184	1.073
1986–87	0.967	0.965	0.965	1.041	1.120	1.111	0.980	1.013	1.092	0.993
1987–88	0.847	0.937	0.956	1.054	1.043	0.964	1.051	1.073	1.123	1.004
1988–89	0.920	0.924	1.044	1.019	1.069	1.060	1.157	1.032	0.914	1.015
1989–90	0.907	0.969	0.962	0.987	0.989	1.078	1.055	1.137	1.009	0.992
1990–91	0.862	0.992	0.994	0.989	0.975	0.939	0.965	0.987	0.919	0.900
1991–92	0.912	0.931	0.950	0.951	0.934	1.002	1.042	0.982	1.111	1.059
1992–93	0.900	0.933	0.982	0.955	0.967	1.023	1.040	0.991	0.938	0.943
1993–94	0.966	0.975	1.022	0.994	1.079	1.123	1.060	1.100	1.047	1.051
1994–95	0.976	0.995	1.011	1.086	1.198	1.120	1.040	1.104	1.090	1.098
1995–96	0.891	0.988	1.029	1.011	1.036	0.960	1.047	1.171	1.238	1.283
1996–97	0.927	1.013	1.064	1.050	1.108	1.146	1.323	1.214	1.097	1.067
1997–98	0.987	1.072	1.004	1.020	1.079	1.100	1.016	1.070	1.086	1.040
1998–99	0.894	0.955	1.017	0.976	0.987	0.970	1.042	1.017	1.023	0.864
1999–00	0.850	0.954	0.945	0.924	0.954	0.956	1.014	0.892	0.959	0.948
2000–01	0.879	0.880	0.931	0.954	0.896	0.951	1.014	1.080	1.028	0.977
2001–02	0.844	0.880	0.933	0.861	0.898	0.889	0.964	0.968	1.001	0.977
2002–03	0.852	0.874	0.906	0.881	0.872	0.911	0.985	1.063	0.981	0.961
2003–04	0.799	0.836	0.912	0.893	0.907	0.931	1.016	1.071	0.912	0.880
2004–05	0.853	0.885	0.890	0.942	0.958	0.927	1.019	1.062	0.931	0.903
2005–06	0.827	0.904	0.936	0.903	0.931	1.109	1.012	1.067	1.006	0.977
2006–07	0.820	0.896	0.959	0.920	0.907	0.938	0.984	1.057	0.978	0.927
2007–08	0.823	0.887	0.920	0.930	0.928	0.970	1.097	1.057	1.057	0.948
2008–09	0.841	0.925	0.969	0.917	0.986	1.015	1.182	1.130	1.013	0.973
2009–10	0.858	0.922	0.914	0.930	0.911	0.971	0.979	0.969	0.963	0.900
2010–11	0.828	0.884	0.856	0.799	0.865	0.849	0.896	0.919	0.919	0.862
2011–12	0.803	0.840	0.835	0.791	0.886	0.871	0.904	0.901	0.946	0.944
Queenscliff Region										
1978–79	1.065	1.007	1.064	0.976	0.971	1.055	1.052	1.378	0.983	0.989
1979–80	0.977	1.034	0.990	0.901	0.961	0.957	1.150	1.208	0.877	0.913
1980–81	0.984	1.017	0.988	0.947	0.989	0.998	1.156	1.270	0.865	0.916
1981–82	0.848	0.906	0.917	0.967	1.012	1.054	0.899	1.043	1.004	0.985
1982–83	0.923	0.998	0.969	0.931	1.013	1.038	1.343	1.267	0.938	0.984
1983–84	0.913	0.989	0.992	0.970	0.981	1.021	1.026	1.643	0.987	0.985
1984–85	1.001	1.108	1.126	1.091	1.145	1.218	1.185	1.527	1.009	1.083
1985–86	0.975	1.120	1.110	1.131	1.120	1.192	1.457	1.131	1.125	1.025
1986–87	0.995	1.016	1.134	1.110	1.114	1.157	1.363	1.305	1.144	1.033
1987–88	0.907	1.008	1.107	1.135	1.081	1.151	1.394	1.059	1.087	0.973
1988–89	0.893	1.011	0.973	0.987	1.044	1.068	1.060	1.264	0.919	0.934
1989–90	0.840	0.973	0.968	0.908	0.920	0.927	0.989	0.999	0.929	0.923
1990–91	0.890	0.965	0.993	0.938	0.916	0.995	0.900	0.912	0.869	0.834
1991–92	0.845	0.933	0.918	0.946	0.980	1.030	1.021	1.200	1.019	0.946
1992–93	0.887	0.911	0.942	0.917	0.957	1.128	1.026	1.345	1.142	1.082
1993–94	0.889	1.042	1.058	1.045	1.112	1.187	1.269	1.456	1.149	0.995
1994–95	1.026	1.123	1.098	1.148	1.145	1.098	1.315	1.470	1.026	1.017
1995–96	0.933	1.079	1.095	1.158	1.157	1.286	1.402	1.187	1.200	1.074
1996–97	1.006	1.095	1.267	1.230	1.163	1.204	1.140	1.013	1.036	1.099
1997–98	1.027	1.199	1.078	1.062	1.131	1.163	0.982	1.351	1.016	1.011
1998–99	1.041	1.098	1.078	0.999	0.993	1.084	1.172	1.241	0.990	0.930
1999–00	0.955	0.913	0.899	0.895	0.961	1.037	1.096	1.033	1.019	0.911
2000–01	0.887	0.941	0.974	0.963	0.972	0.992	1.035	1.012	1.049	1.074
2001–02	0.925	1.002	0.945	0.912	0.938	0.913	1.090	1.197	1.108	0.985
2002–03	0.912	1.068	1.026	1.034	0.988	0.989	1.214	1.344	1.074	0.945
2003–04	0.836	0.959	1.038	0.957	0.988	1.113	1.136	1.451	1.076	1.025
2004–05	0.882	1.082	0.985	1.025	1.041	1.122	1.403	1.787	1.270	1.026
2005–06	0.853	1.022	1.054	1.038	1.120	1.087	1.107	1.302	1.138	0.965
2006–07	0.834	0.965	1.022	1.016	1.029	1.020	1.310	1.442	1.212	1.055
2007–08	0.869	1.017	1.094	1.164	1.104	1.017	1.158	1.242	1.159	0.989
2008–09	0.870	1.068	1.100	1.242	1.233	1.169	1.541	1.253	1.216	1.016
2009–10	0.973	1.104	1.081	1.132	1.080	1.100	1.103	1.266	0.968	0.851
2010–11	0.777	1.007	0.936	0.868	0.884	0.893	1.237	1.109	0.937	0.864
2011–12	0.844	0.986	1.007	0.935	0.966	0.928	1.034	1.428	1.158	0.961

Data source: Fisheries Victoria CandE Database (11 January 2013)

Table 10.2.3. Monthly mean mass per SRL during fishing years from 1978–79 to 2011–12 by region

Data: non-screened and non-selected; SRL, southern rock lobster.

Fishing year	Mean mass per SRL (kg) for each month									
	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug–Sep
San Remo Region										
1978–79	1.236	1.299	1.373	1.294	1.310	1.367	1.539	1.474	1.641	1.447
1979–80	1.147	1.158	1.286	1.256	0.981	1.488	1.403	1.574	1.600	1.459
1980–81	1.074	1.269	1.271	1.334	1.335	1.269	1.464	1.850	1.628	1.220
1981–82	1.088	1.314	1.317	1.290	1.265	1.193	1.457	1.395	1.666	1.468
1982–83	1.142	1.214	1.160	1.199	1.254	1.278	1.365	1.405	1.500	1.283
1983–84	1.111	1.150	1.189	1.129	1.262	1.271	1.396	1.569	1.304	1.428
1984–85	1.083	1.284	1.206	1.216	1.252	1.404	1.665	1.595	1.824	1.507
1985–86	1.216	1.229	1.220	1.345	1.363	1.413	1.296	1.434	1.633	1.602
1986–87	1.244	1.203	1.311	1.327	1.301	1.152	1.502	2.252	1.366	1.392
1987–88	1.173	1.395	1.328	1.030	1.116	1.232	1.432	1.234	1.452	1.335
1988–89	1.157	1.115	1.136	1.108	1.187	1.259	1.269	1.804	1.428	1.422
1989–90	1.210	1.078	1.120	1.115	1.146	0.967	1.113	1.440	1.264	1.300
1990–91	1.053	1.034	1.138	1.134	1.160	1.179	1.113	1.373	1.070	1.146
1991–92	1.188	1.162	0.997	1.129	1.167	1.132	1.137	1.190	1.393	1.468
1992–93	1.107	1.124	1.101	1.163	1.311	1.289	1.318	1.585	1.485	1.476
1993–94	1.291	1.252	1.324	1.368	1.358	1.456	1.459	1.796	1.690	1.634
1994–95	1.361	1.324	1.382	1.391	1.314	1.410	1.725	1.572	1.640	1.617
1995–96	1.216	1.290	1.305	1.313	1.389	1.466	1.421	1.511	1.694	1.584
1996–97	1.281	1.375	1.353	1.431	1.426	1.503	1.559	1.739	1.710	1.657
1997–98	1.275	1.400	1.385	1.389	1.456	1.510	1.504	1.706	1.516	1.393
1998–99	1.296	1.371	1.283	1.185	1.329	1.367	1.394	1.669	1.592	1.381
1999–00	1.207	1.239	1.174	1.295	1.361	1.426	1.556	1.468	1.663	1.498
2000–01	1.190	1.263	1.306	1.332	1.453	1.527	1.505	1.531	1.475	1.490
2001–02	1.218	1.296	1.315	1.185	1.412	1.451	1.461	1.781	1.648	1.569
2002–03	1.085	1.198	1.268	1.212	1.252	1.326	1.404	1.787	1.740	1.573
2003–04	1.024	1.295	1.396	1.244	1.457	1.462	1.591	2.185	1.709	1.685
2004–05	1.218	1.307	1.527	1.304	1.463	1.463	1.557	1.860	1.652	1.446
2005–06	1.190	1.266	1.250	1.254	1.372	1.438	1.535	1.702	1.424	1.435
2006–07	1.188	1.208	1.249	1.255	1.400	1.324	1.171	1.747	1.621	1.547
2007–08	1.140	1.222	1.310	1.285	1.426	1.350	1.345	1.998	1.814	1.814
2008–09	1.187	1.348	1.344	1.352	1.321	1.379	1.551	1.815	1.775	1.882
2009–10	1.227	1.287	1.248	1.241	1.334	1.412	1.672	1.604	1.473	1.390
2010–11	1.070	1.194	1.206	1.053	1.204	1.101	1.438	1.364	1.558	1.488
2011–12	1.100	1.198	1.504	1.302	1.177	1.345	1.526	1.337	1.790	1.638
Lakes Entrance Region										
1978–79	1.112	1.172	1.245	1.275	1.063	1.010	1.174	1.174	1.532	0.986
1979–80	1.041	1.182	1.137	1.419	1.222	1.308	1.217	1.225	1.194	1.307
1980–81	1.091	1.115	1.097	1.207	1.076	1.358	1.304	1.102	1.102	0.564
1981–82	1.181	1.139	1.251	1.005	0.992	1.069	1.090	1.090	1.050	1.036
1982–83	1.143	1.222	1.140	1.187	1.189	1.189	1.189	1.250	1.189	1.189
1983–84	1.104	1.296	1.430	1.540	1.500	1.466	1.250	1.370	1.370	1.370
1984–85	1.137	1.235	1.343	1.223	1.201	0.976	1.216	1.216	1.400	1.216
1985–86	1.193	1.214	1.440	1.250	1.250	1.246	1.825	1.309	1.089	1.279
1986–87	1.267	1.365	1.298	1.381	1.157	1.363	1.363	1.363	1.686	1.390
1987–88	1.174	1.284	1.149	1.169	1.018	1.206	1.046	1.410	1.684	0.920
1988–89	1.141	1.095	1.237	1.116	1.072	1.384	1.149	1.149	1.202	0.947
1989–90	1.025	1.011	1.001	1.115	1.207	1.094	1.250	1.500	1.544	1.129
1990–91	1.161	1.178	1.307	1.025	0.973	1.069	1.119	1.119	1.119	1.119
1991–92	1.186	1.275	1.389	1.179	1.269	1.259	1.259	1.259	1.259	1.259
1992–93	1.246	1.367	1.344	1.267	1.421	1.090	1.547	1.326	1.326	1.326
1993–94	1.227	1.038	1.119	1.160	1.237	1.275	1.235	2.667	2.333	1.164
1994–95	1.140	1.150	1.259	1.336	1.342	1.447	1.563	1.325	1.034	1.118
1995–96	1.072	1.160	1.160	1.132	0.941	0.841	1.111	1.108	1.137	1.054
1996–97	1.138	1.166	1.195	1.088	1.349	1.264	1.111	1.181	1.175	1.248
1997–98	1.235	1.268	1.176	1.181	1.221	1.196	1.409	1.123	1.252	1.243
1998–99	1.159	1.259	1.316	1.389	1.129	1.121	1.118	1.000	1.235	1.192
1999–00	1.106	1.151	1.136	1.140	1.151	1.292	1.355	1.087	1.178	1.329
2000–01	1.114	1.181	1.228	1.200	1.058	1.099	0.923	1.043	1.106	1.106
2001–02	0.935	1.083	1.065	1.024	1.313	1.152	1.101	1.139	1.114	1.212
2002–03	1.146	1.153	1.300	1.237	1.218	1.000	1.322	1.322	1.322	2.200
2003–04	1.337	1.167	1.312	1.187	2.033	1.458	1.458	1.590	1.560	1.478
2004–05	0.989	1.182	1.300	1.431	1.196	1.329	1.307	1.533	1.252	1.000
2005–06	1.289	1.229	1.147	1.469	1.340	1.067	1.771	1.330	1.330	1.330
2006–07	1.021	1.053	1.417	1.116	1.418	0.809	1.139	1.139	1.139	1.139
2007–08	1.163	1.318	0.977	1.619	1.638	1.625	1.390	1.390	1.390	1.390
2008–09	1.386	1.687	1.669	1.614	1.745	2.156	1.837	1.837	2.600	1.837
2009–10	1.209	1.443	1.591	1.406	1.498	1.498	1.840	1.498	1.498	1.498
2010–11	1.349	1.578	1.455	1.371	1.867	2.017	1.606	1.606	1.606	1.606
2011–12	1.164	1.392	1.510	1.459	1.392	1.606	1.484	1.484	1.484	1.867

Data source: Fisheries Victoria CandE Database (11 January 2013)

Table 11.1.1. Monthly mean nominal-targeted-CPUE during fishing years from 1978–79 to 2011–12 for each zone

Data: non-screened and non-selected; CPUE, nominal catch per unit effort targeted at SRL or both SRL and GC; SRL, southern rock lobster; GC, giant crab.

Fishing year	Mean nominal-targeted-CPUE (kg per potlift) for each month									
	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug–Sep
Western Zone										
1978–79	0.807	1.117	0.967	0.989	0.802	0.613	0.575	0.457	0.360	0.543
1979–80	0.836	0.968	1.072	0.907	0.808	0.724	0.484	0.462	0.418	0.503
1980–81	0.860	1.025	1.012	0.966	0.785	0.693	0.509	0.436	0.379	0.471
1981–82	0.826	0.988	1.022	0.919	0.796	0.617	0.390	0.427	0.404	0.497
1982–83	0.895	1.085	0.921	0.884	0.723	0.669	0.413	0.294	0.431	0.496
1983–84	0.755	0.971	0.988	0.873	0.650	0.524	0.478	0.297	0.466	0.563
1984–85	0.685	0.789	0.891	0.997	0.754	0.541	0.440	0.398	0.342	0.446
1985–86	0.688	0.693	0.739	0.797	0.731	0.525	0.442	0.253	0.300	0.459
1986–87	0.635	0.720	0.710	0.744	0.731	0.557	0.400	0.319	0.312	0.390
1987–88	0.697	0.704	0.817	0.742	0.659	0.518	0.380	0.293	0.264	0.380
1988–89	0.559	0.668	0.683	0.592	0.603	0.470	0.373	0.280	0.291	0.345
1989–90	0.602	0.665	0.694	0.661	0.590	0.459	0.341	0.281	0.310	0.318
1990–91	0.497	0.575	0.622	0.618	0.564	0.442	0.342	0.252	0.280	0.300
1991–92	0.590	0.648	0.754	0.740	0.663	0.551	0.417	0.299	0.252	0.345
1992–93	0.548	0.645	0.748	0.634	0.631	0.542	0.436	0.263	0.269	0.305
1993–94	0.739	0.788	0.702	0.822	0.775	0.543	0.397	0.302	0.270	0.317
1994–95	0.602	0.771	0.796	0.713	0.624	0.467	0.368	0.271	0.241	0.304
1995–96	0.560	0.734	0.829	0.788	0.665	0.427	0.385	0.287	0.265	0.279
1996–97	0.572	0.662	0.714	0.730	0.592	0.465	0.349	0.257	0.251	0.293
1997–98	0.615	0.832	0.806	0.701	0.621	0.510	0.369	0.275	0.259	0.354
1998–99	0.696	0.833	0.800	0.765	0.732	0.594	0.394	0.276	0.315	0.379
1999–00	0.766	0.810	0.804	0.802	0.650	0.528	0.383	0.227	0.316	0.399
2000–01	0.834	0.813	0.854	0.783	0.598	0.473	0.392	0.256	0.309	0.356
2001–02	0.766	0.786	0.914	0.862	0.758	0.573	0.447	0.264	0.285	0.385
2002–03	0.827	0.910	1.003	0.847	0.739	0.684	0.511	0.311	0.320	0.426
2003–04	0.935	0.869	0.901	0.963	0.836	0.729	0.530	0.361	0.346	0.382
2004–05	0.826	0.854	0.820	0.807	0.709	0.625	0.427	0.293	0.259	0.349
2005–06	0.659	0.631	0.778	0.669	0.532	0.431	0.268	0.204	0.290	0.319
2006–07	0.554	0.613	0.608	0.685	0.563	0.448	0.289	0.000	0.000	0.321
2007–08	0.610	0.535	0.582	0.551	0.502	0.360	0.279	0.000	0.000	0.225
2008–09	0.489	0.590	0.539	0.506	0.446	0.311	0.265	0.251	0.233	0.222
2009–10	0.449	0.470	0.487	0.502	0.406	0.330	0.275	0.205	0.219	0.262
2010–11	0.550	0.479	0.573	0.537	0.482	0.381	0.303	0.250	0.366	0.326
2011–12	0.561	0.599	0.615	0.573	0.472	0.398	0.337	0.319	0.345	0.404
Eastern Zone										
1978–79	0.777	0.748	0.966	0.691	0.551	0.535	0.567	0.414	0.464	0.631
1979–80	0.695	0.847	0.804	0.751	0.549	0.482	0.590	0.471	0.533	0.588
1980–81	0.883	0.864	0.866	0.789	0.563	0.558	0.568	0.354	0.439	0.542
1981–82	0.695	0.784	0.748	0.703	0.578	0.530	0.543	0.331	0.450	0.534
1982–83	0.939	0.858	0.818	0.811	0.606	0.526	0.534	0.429	0.437	0.562
1983–84	0.630	0.728	0.765	0.676	0.552	0.521	0.402	0.315	0.311	0.463
1984–85	0.641	0.680	0.668	0.708	0.576	0.506	0.406	0.283	0.316	0.406
1985–86	0.704	0.643	0.627	0.556	0.517	0.532	0.422	0.289	0.390	0.397
1986–87	0.657	0.643	0.557	0.555	0.514	0.378	0.389	0.429	0.484	0.443
1987–88	0.570	0.666	0.693	0.536	0.536	0.483	0.532	0.324	0.291	0.333
1988–89	0.640	0.568	0.550	0.459	0.443	0.475	0.163	0.269	0.302	0.383
1989–90	0.629	0.502	0.511	0.473	0.411	0.282	0.207	0.185	0.307	0.412
1990–91	0.534	0.504	0.492	0.502	0.395	0.281	0.252	0.236	0.333	0.417
1991–92	0.515	0.426	0.397	0.442	0.361	0.323	0.263	0.229	0.208	0.306
1992–93	0.410	0.436	0.386	0.324	0.325	0.282	0.292	0.238	0.211	0.216
1993–94	0.453	0.400	0.377	0.351	0.303	0.199	0.242	0.178	0.202	0.218
1994–95	0.305	0.375	0.353	0.331	0.288	0.248	0.339	0.245	0.194	0.193
1995–96	0.287	0.359	0.328	0.320	0.310	0.394	0.330	0.182	0.171	0.162
1996–97	0.252	0.328	0.337	0.333	0.362	0.325	0.239	0.196	0.204	0.287
1997–98	0.451	0.450	0.363	0.300	0.318	0.273	0.213	0.188	0.190	0.252
1998–99	0.379	0.439	0.410	0.358	0.259	0.276	0.228	0.189	0.227	0.315
1999–00	0.376	0.429	0.414	0.409	0.290	0.270	0.205	0.176	0.213	0.313
2000–01	0.486	0.439	0.366	0.351	0.255	0.280	0.218	0.220	0.268	0.328
2001–02	0.409	0.444	0.474	0.405	0.370	0.315	0.227	0.180	0.261	0.310
2002–03	0.455	0.502	0.458	0.421	0.299	0.404	0.270	0.302	0.276	0.445
2003–04	0.557	0.528	0.465	0.435	0.369	0.366	0.314	0.286	0.279	0.408
2004–05	0.526	0.565	0.504	0.400	0.393	0.382	0.294	0.377	0.285	0.340
2005–06	0.476	0.484	0.567	0.427	0.411	0.318	0.323	0.304	0.321	0.346
2006–07	0.437	0.496	0.522	0.495	0.406	0.315	0.303	0.250	0.252	0.321
2007–08	0.425	0.451	0.422	0.381	0.344	0.369	0.214	0.209	0.357	0.359
2008–09	0.402	0.467	0.433	0.391	0.388	0.330	0.301	0.242	0.312	0.266
2009–10	0.428	0.455	0.436	0.413	0.313	0.234	0.265	0.253	0.339	0.496
2010–11	0.532	0.536	0.538	0.432	0.390	0.406	0.341	0.182	0.386	0.456
2011–12	0.550	0.612	0.576	0.397	0.339	0.423	0.407	0.260	0.535	0.582

Data source: Fisheries Victoria CandE Database (11 January 2013)

Table 11.2.1. Monthly mean nominal-targeted-CPUE during fishing years from 1978–79 to 2011–12 for each region

Data: non-screened and non-selected; CPUE, nominal catch per unit effort targeted at SRL or both SRL and GC; SRL, southern rock lobster; GC, giant crab.

Fishing year	Mean nominal-targeted-CPUE (kg per potlift) for each month									
	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug–Sep
Portland Region										
1978–79	0.673	0.962	0.895	0.775	0.713	0.539	0.486	0.408	0.369	0.479
1979–80	0.681	0.752	0.861	0.716	0.701	0.501	0.320	0.421	0.340	0.506
1980–81	0.834	1.003	0.946	0.950	0.677	0.567	0.413	0.510	0.365	0.404
1981–82	0.701	0.843	0.963	0.836	0.791	0.593	0.393	0.398	0.393	0.487
1982–83	0.776	0.876	0.866	0.850	0.753	0.702	0.408	0.214	0.423	0.418
1983–84	0.651	0.766	0.820	0.755	0.599	0.502	0.386	0.235	0.464	0.497
1984–85	0.594	0.723	0.747	0.854	0.672	0.486	0.338	0.666	0.381	0.403
1985–86	0.644	0.621	0.717	0.725	0.699	0.546	0.518	0.334	0.353	0.420
1986–87	0.643	0.742	0.680	0.671	0.660	0.474	0.363	0.219	0.282	0.342
1987–88	0.695	0.710	0.885	0.713	0.612	0.512	0.326	0.466	0.276	0.394
1988–89	0.513	0.713	0.632	0.552	0.578	0.425	0.379	0.264	0.279	0.366
1989–90	0.621	0.656	0.700	0.657	0.567	0.459	0.390	0.243	0.311	0.264
1990–91	0.459	0.506	0.574	0.571	0.568	0.411	0.306	0.215	0.270	0.307
1991–92	0.611	0.668	0.762	0.733	0.625	0.488	0.391	0.256	0.226	0.288
1992–93	0.467	0.557	0.655	0.534	0.501	0.450	0.360	0.191	0.211	0.244
1993–94	0.631	0.698	0.638	0.683	0.634	0.459	0.343	0.237	0.229	0.288
1994–95	0.517	0.740	0.762	0.705	0.603	0.420	0.323	0.207	0.220	0.283
1995–96	0.568	0.709	0.764	0.710	0.634	0.405	0.318	0.201	0.214	0.231
1996–97	0.591	0.631	0.664	0.654	0.533	0.412	0.316	0.231	0.222	0.275
1997–98	0.527	0.761	0.809	0.674	0.557	0.462	0.350	0.241	0.256	0.354
1998–99	0.656	0.734	0.769	0.655	0.625	0.550	0.350	0.250	0.271	0.322
1999–00	0.757	0.739	0.771	0.744	0.598	0.454	0.345	0.228	0.267	0.315
2000–01	0.749	0.779	0.776	0.697	0.557	0.417	0.325	0.246	0.261	0.332
2001–02	0.681	0.788	0.870	0.812	0.681	0.562	0.448	0.302	0.290	0.376
2002–03	0.920	0.932	0.984	0.859	0.750	0.747	0.544	0.285	0.322	0.371
2003–04	1.083	0.882	0.917	1.002	0.914	0.786	0.525	0.287	0.321	0.372
2004–05	0.936	0.919	0.947	0.978	0.779	0.702	0.428	0.264	0.282	0.345
2005–06	0.612	0.589	0.688	0.617	0.499	0.375	0.256	0.169	0.266	0.269
2006–07	0.499	0.513	0.524	0.584	0.496	0.383	0.287	0.000	0.000	0.276
2007–08	0.592	0.470	0.557	0.457	0.417	0.299	0.219	0.000	0.000	0.207
2008–09	0.455	0.507	0.465	0.384	0.364	0.286	0.196	0.186	0.203	0.209
2009–10	0.422	0.406	0.434	0.404	0.342	0.334	0.277	0.233	0.206	0.240
2010–11	0.483	0.459	0.549	0.521	0.429	0.355	0.282	0.233	0.316	0.284
2011–12	0.526	0.507	0.508	0.457	0.456	0.376	0.314	0.226	0.276	0.343
Warrnambool Region										
1978–79	0.536	0.977	0.949	1.059	0.791	0.618	0.562	0.411	0.324	0.472
1979–80	0.564	0.815	1.186	1.032	0.868	0.775	0.427	0.499	0.480	0.419
1980–81	0.613	0.792	0.877	0.814	0.704	0.666	0.477	0.246	0.344	0.374
1981–82	0.535	0.739	0.916	0.959	0.807	0.625	0.339	0.384	0.386	0.459
1982–83	0.637	0.855	0.823	0.896	0.680	0.567	0.326	0.324	0.402	0.843
1983–84	0.593	1.035	1.237	1.053	0.728	0.529	0.448	0.307	0.358	0.627
1984–85	0.611	0.678	0.973	1.169	0.817	0.570	0.390	0.248	0.317	0.459
1985–86	0.547	0.589	0.665	0.806	0.695	0.481	0.323	0.239	0.168	0.404
1986–87	0.467	0.546	0.755	0.747	0.657	0.545	0.390	0.305	0.329	0.431
1987–88	0.680	0.527	0.685	0.701	0.639	0.482	0.345	0.170	0.220	0.281
1988–89	0.401	0.464	0.578	0.539	0.475	0.393	0.298	0.230	0.301	0.285
1989–90	0.334	0.447	0.534	0.555	0.532	0.394	0.263	0.277	0.281	0.368
1990–91	0.381	0.510	0.573	0.538	0.523	0.483	0.366	0.294	0.293	0.252
1991–92	0.372	0.515	0.710	0.617	0.700	0.658	0.419	0.316	0.285	0.367
1992–93	0.403	0.587	0.797	0.757	0.762	0.606	0.493	0.330	0.312	0.328
1993–94	0.505	0.583	0.654	0.905	0.954	0.606	0.387	0.307	0.304	0.305
1994–95	0.471	0.612	0.741	0.618	0.515	0.453	0.394	0.297	0.236	0.328
1995–96	0.456	0.611	0.833	0.892	0.637	0.433	0.494	0.333	0.353	0.321
1996–97	0.485	0.612	0.767	0.781	0.656	0.451	0.329	0.288	0.254	0.254
1997–98	0.519	0.612	0.679	0.610	0.624	0.531	0.338	0.276	0.246	0.311
1998–99	0.652	0.925	0.814	0.859	0.827	0.629	0.419	0.287	0.340	0.381
1999–00	0.600	0.729	0.793	0.793	0.652	0.582	0.398	0.209	0.330	0.418
2000–01	0.705	0.728	0.851	0.790	0.599	0.531	0.420	0.241	0.343	0.333
2001–02	0.576	0.590	0.793	0.794	0.731	0.541	0.351	0.216	0.191	0.319
2002–03	0.550	0.656	0.866	0.676	0.623	0.489	0.305	0.386	0.263	0.380
2003–04	0.559	0.520	0.693	0.789	0.654	0.596	0.518	0.374	0.346	0.376
2004–05	0.518	0.659	0.676	0.698	0.723	0.555	0.378	0.268	0.214	0.303
2005–06	0.597	0.589	0.869	0.716	0.575	0.415	0.258	0.217	0.267	0.272
2006–07	0.518	0.567	0.617	0.681	0.542	0.460	0.221	0.000	0.000	0.359
2007–08	0.534	0.535	0.587	0.623	0.554	0.416	0.312	0.000	0.000	0.175
2008–09	0.435	0.587	0.574	0.586	0.471	0.280	0.265	0.331	0.282	0.241
2009–10	0.352	0.467	0.506	0.606	0.467	0.318	0.265	0.163	0.210	0.261
2010–11	0.541	0.491	0.589	0.563	0.608	0.409	0.287	0.295	0.417	0.366
2011–12	0.499	0.650	0.751	0.766	0.440	0.368	0.265	0.368	0.484	0.517

Data source: Fisheries Victoria CandE Database (11 January 2013)

Table 11.2.2. Monthly mean nominal-targeted-CPUE during fishing years from 1978–79 to 2011–12 for each region

Data: non-screened and non-selected; CPUE, nominal catch per unit effort targeted at SRL or both SRL and GC; SRL, southern rock lobster; GC, giant crab.

Fishing year	Mean nominal-targeted-CPUE (kg per potlift) for each month									
	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug–Sep
Apollo Bay Region										
1978–79	1.277	1.562	1.186	1.411	1.135	0.960	0.857	0.663	0.456	1.114
1979–80	1.396	1.704	1.390	1.212	1.122	1.274	0.806	0.498	0.847	0.668
1980–81	1.265	1.387	1.305	1.195	1.331	1.189	0.785	0.716	0.585	0.798
1981–82	1.252	1.460	1.278	1.068	0.791	0.687	0.533	0.603	0.509	0.558
1982–83	1.329	1.661	1.214	0.977	0.674	0.734	0.637	0.345	0.569	0.544
1983–84	1.147	1.412	1.168	0.933	0.672	0.565	0.622	0.297	0.621	0.716
1984–85	0.964	1.026	1.107	1.096	0.866	0.652	0.646	0.535	0.300	0.573
1985–86	0.927	0.952	0.877	0.973	0.869	0.553	0.554	0.216	0.481	0.632
1986–87	0.775	0.828	0.732	0.900	1.006	0.780	0.464	0.452	0.399	0.430
1987–88	0.722	0.911	0.863	0.875	0.826	0.591	0.491	0.330	0.350	0.476
1988–89	0.892	0.829	0.948	0.772	0.870	0.720	0.495	0.360	0.308	0.363
1989–90	0.793	0.908	0.855	0.795	0.741	0.557	0.365	0.340	0.337	0.454
1990–91	0.701	0.872	0.843	0.862	0.591	0.534	0.408	0.265	0.300	0.357
1991–92	0.781	0.731	0.788	0.905	0.758	0.678	0.505	0.426	0.343	0.556
1992–93	0.900	0.988	0.979	0.925	0.934	0.791	0.732	0.453	0.441	0.489
1993–94	1.161	1.222	0.963	1.101	0.983	0.763	0.605	0.520	0.381	0.428
1994–95	0.880	0.985	0.957	0.828	0.798	0.677	0.543	0.520	0.441	0.375
1995–96	0.630	0.936	1.079	0.997	0.843	0.542	0.542	0.508	0.390	0.460
1996–97	0.588	0.815	0.815	0.926	0.729	0.635	0.516	0.312	0.353	0.403
1997–98	0.896	1.148	0.897	0.872	0.821	0.700	0.478	0.417	0.294	0.411
1998–99	0.868	1.032	0.863	0.883	0.863	0.680	0.543	0.347	0.478	0.558
1999–00	0.962	1.118	0.939	0.977	0.828	0.683	0.550	0.258	0.465	0.599
2000–01	1.172	0.994	1.085	1.045	0.739	0.590	0.550	0.303	0.434	0.453
2001–02	1.086	0.988	1.158	1.079	0.959	0.635	0.569	0.233	0.395	0.477
2002–03	0.949	1.202	1.240	1.063	0.886	0.841	0.659	0.312	0.447	0.568
2003–04	0.982	1.125	1.103	1.068	0.877	0.757	0.562	0.566	0.442	0.414
2004–05	0.910	0.912	0.785	0.695	0.588	0.534	0.496	0.403	0.318	0.447
2005–06	0.840	0.779	0.886	0.738	0.555	0.703	0.334	0.298	0.523	0.488
2006–07	0.710	0.883	0.794	0.912	0.758	0.601	0.371	0.000	0.000	0.419
2007–08	0.727	0.661	0.638	0.690	0.635	0.469	0.467	0.000	0.000	0.358
2008–09	0.629	0.763	0.633	0.628	0.571	0.382	0.372	0.252	0.311	0.248
2009–10	0.615	0.614	0.547	0.536	0.453	0.343	0.286	0.196	0.340	0.340
2010–11	0.708	0.522	0.605	0.537	0.548	0.449	0.386	0.252	0.490	0.412
2011–12	0.687	0.717	0.657	0.633	0.562	0.479	0.384	0.429	0.483	0.456
Queenscliff Region										
1978–79	0.612	0.669	0.977	0.586	0.414	0.469	0.509	0.211	0.448	0.691
1979–80	0.685	0.793	0.771	0.697	0.485	0.336	0.713	0.260	0.488	0.610
1980–81	0.895	0.761	0.832	0.718	0.479	0.438	0.451	0.096	0.342	0.538
1981–82	0.614	0.545	0.647	0.572	0.469	0.502	0.632	0.216	0.296	0.473
1982–83	0.836	0.695	0.747	0.733	0.563	0.466	0.500	0.235	0.348	0.602
1983–84	0.637	0.646	0.773	0.699	0.513	0.534	0.369	0.257	0.263	0.451
1984–85	0.528	0.579	0.622	0.595	0.553	0.537	0.382	0.240	0.136	0.404
1985–86	0.576	0.543	0.523	0.581	0.460	0.511	0.279	0.344	0.269	0.398
1986–87	0.493	0.475	0.508	0.495	0.481	0.441	0.294	0.516	0.491	0.467
1987–88	0.505	0.550	0.584	0.511	0.548	0.643	0.972	0.299	0.252	0.321
1988–89	0.535	0.463	0.480	0.464	0.491	0.567	0.171	0.367	0.286	0.423
1989–90	0.547	0.495	0.534	0.496	0.401	0.291	0.250	0.262	0.322	0.415
1990–91	0.445	0.440	0.436	0.444	0.362	0.273	0.213	0.225	0.340	0.427
1991–92	0.450	0.379	0.386	0.472	0.359	0.307	0.277	0.207	0.201	0.292
1992–93	0.461	0.374	0.323	0.290	0.279	0.261	0.340	0.187	0.174	0.198
1993–94	0.459	0.382	0.314	0.306	0.290	0.160	0.294	0.171	0.168	0.214
1994–95	0.247	0.311	0.283	0.284	0.238	0.176	0.436	0.364	0.162	0.188
1995–96	0.287	0.316	0.279	0.292	0.311	0.459	0.433	0.137	0.151	0.156
1996–97	0.186	0.239	0.284	0.304	0.337	0.370	0.257	0.140	0.146	0.285
1997–98	0.409	0.386	0.353	0.271	0.269	0.253	0.171	0.166	0.173	0.257
1998–99	0.379	0.407	0.397	0.346	0.250	0.315	0.249	0.175	0.224	0.355
1999–00	0.361	0.408	0.441	0.436	0.292	0.290	0.209	0.173	0.191	0.340
2000–01	0.484	0.411	0.339	0.285	0.234	0.259	0.235	0.184	0.251	0.345
2001–02	0.431	0.438	0.509	0.417	0.289	0.305	0.170	0.207	0.238	0.316
2002–03	0.406	0.483	0.473	0.444	0.304	0.439	0.307	0.179	0.257	0.489
2003–04	0.555	0.499	0.456	0.441	0.302	0.412	0.349	0.305	0.257	0.415
2004–05	0.513	0.532	0.470	0.381	0.343	0.415	0.293	0.190	0.264	0.316
2005–06	0.417	0.463	0.501	0.391	0.294	0.282	0.341	0.157	0.243	0.332
2006–07	0.412	0.437	0.495	0.474	0.334	0.278	0.341	0.178	0.217	0.339
2007–08	0.437	0.427	0.401	0.340	0.322	0.359	0.221	0.111	0.257	0.331
2008–09	0.419	0.415	0.391	0.310	0.370	0.262	0.200	0.170	0.298	0.258
2009–10	0.411	0.417	0.410	0.357	0.261	0.198	0.282	0.145	0.287	0.495
2010–11	0.541	0.494	0.582	0.422	0.397	0.434	0.394	0.191	0.356	0.446
2011–12	0.564	0.569	0.512	0.330	0.260	0.404	0.435	0.293	0.462	0.603

Data source: Fisheries Victoria CandE Database (11 January 2013)

Table 11.2.3. Monthly mean nominal-targeted-CPUE during fishing years from 1978–79 to 2011–12 for each region

Data: non-screened and non-selected; CPUE, nominal catch per unit effort targeted at SRL or both SRL and GC; SRL, southern rock lobster; GC, giant crab.

Fishing year	Mean nominal-targeted-CPUE (kg per potlift) for each month									
	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug–Sep
San Remo Region										
1978–79	0.557	0.632	0.862	0.674	0.662	0.556	0.611	0.441	0.490	0.478
1979–80	0.544	0.622	0.739	0.769	0.533	0.581	0.426	0.799	0.632	0.485
1980–81	0.621	0.793	0.788	0.775	0.668	0.692	0.649	0.443	0.648	0.559
1981–82	0.589	1.002	0.853	0.828	0.720	0.510	0.467	0.391	0.734	0.693
1982–83	0.771	0.946	0.903	0.899	0.674	0.581	0.562	0.543	0.565	0.486
1983–84	0.460	0.626	0.637	0.578	0.637	0.480	0.433	0.438	0.422	0.495
1984–85	0.433	0.683	0.566	0.698	0.553	0.463	0.423	0.322	0.516	0.412
1985–86	0.446	0.543	0.627	0.462	0.584	0.525	0.476	0.274	0.436	0.357
1986–87	0.610	0.572	0.536	0.597	0.539	0.313	0.447	0.371	0.454	0.332
1987–88	0.487	0.546	0.602	0.446	0.355	0.260	0.233	0.314	0.380	0.231
1988–89	0.322	0.418	0.395	0.368	0.285	0.246	0.158	0.190	0.336	0.269
1989–90	0.390	0.370	0.385	0.327	0.324	0.190	0.131	0.154	0.211	0.284
1990–91	0.300	0.410	0.449	0.421	0.372	0.294	0.265	0.239	0.314	0.393
1991–92	0.381	0.340	0.276	0.368	0.375	0.364	0.254	0.254	0.235	0.347
1992–93	0.268	0.450	0.420	0.316	0.375	0.296	0.256	0.264	0.297	0.254
1993–94	0.367	0.361	0.408	0.407	0.321	0.235	0.179	0.179	0.269	0.227
1994–95	0.250	0.372	0.384	0.314	0.310	0.255	0.235	0.184	0.254	0.200
1995–96	0.218	0.319	0.336	0.338	0.296	0.216	0.194	0.201	0.256	0.176
1996–97	0.202	0.289	0.315	0.265	0.287	0.217	0.225	0.204	0.320	0.278
1997–98	0.329	0.396	0.351	0.300	0.331	0.275	0.232	0.198	0.225	0.245
1998–99	0.286	0.377	0.340	0.306	0.237	0.228	0.197	0.197	0.238	0.240
1999–00	0.330	0.351	0.338	0.316	0.261	0.216	0.180	0.181	0.241	0.226
2000–01	0.296	0.310	0.329	0.459	0.279	0.273	0.187	0.255	0.313	0.271
2001–02	0.327	0.418	0.360	0.356	0.380	0.322	0.275	0.147	0.337	0.269
2002–03	0.293	0.428	0.341	0.324	0.272	0.336	0.205	0.485	0.360	0.317
2003–04	0.397	0.505	0.421	0.365	0.528	0.292	0.230	0.245	0.364	0.386
2004–05	0.496	0.617	0.415	0.469	0.440	0.298	0.255	0.477	0.407	0.384
2005–06	0.573	0.449	0.652	0.470	0.534	0.345	0.314	0.471	0.466	0.382
2006–07	0.436	0.561	0.609	0.509	0.457	0.384	0.212	0.295	0.350	0.306
2007–08	0.331	0.421	0.466	0.424	0.377	0.385	0.201	0.337	0.502	0.400
2008–09	0.357	0.489	0.539	0.484	0.397	0.415	0.382	0.295	0.348	0.280
2009–10	0.381	0.469	0.457	0.485	0.383	0.300	0.241	0.332	0.479	0.499
2010–11	0.427	0.652	0.553	0.490	0.448	0.456	0.290	0.169	0.445	0.474
2011–12	0.540	0.741	0.801	0.527	0.496	0.473	0.383	0.183	0.697	0.558
Lakes Entrance Region										
1978–79	1.775	1.401	1.151	1.283	0.791	0.658			0.515	0.560
1979–80	1.636	1.714	1.211	1.054	1.306	1.189	0.563		0.637	0.861
1980–81	1.427	1.654	1.348	1.426	0.705	0.742	0.357			0.733
1981–82	1.540	1.523	1.137	1.290	0.953	2.519			1.000	0.816
1982–83	2.280	1.900	1.284	1.213				0.469		
1983–84	1.327	1.844	1.275	1.374	0.300	1.650	0.379			
1984–85	1.993	1.492	1.844	2.604	2.069	0.817			0.350	
1985–86	1.922	1.503	1.469	1.227	0.750	0.838	0.519		0.687	0.792
1986–87	1.802	1.782	1.319	1.205	0.953				0.755	1.895
1987–88	1.219	1.913	1.615	1.438	1.948		0.634	0.407	0.762	0.816
1988–89	1.443	1.278	1.456	0.921	0.850	1.067			0.434	0.363
1989–90	1.146	0.928	0.718	1.011	1.698	1.025	0.192	0.154	0.777	0.921
1990–91	1.117	0.922	1.042	1.421	1.118	0.242				
1991–92	0.946	0.689	0.852	0.249	0.197					
1992–93	0.490	0.841	0.727	0.613	0.459	0.520	0.268			
1993–94	0.666	0.742	0.697	0.528	0.336	0.302	0.148	0.267	0.175	0.233
1994–95	0.654	0.644	0.628	0.633	0.457	0.494	0.261	0.137	0.148	0.265
1995–96	0.552	0.953	0.672	0.654	0.362	0.370	0.152	0.350	0.201	0.239
1996–97	0.994	1.095	0.644	0.789	0.740	0.539	0.295	0.286	0.360	0.375
1997–98	0.851	0.834	0.470	0.508	0.744	0.371	0.112	0.161	0.228	0.143
1998–99	0.595	0.693	0.619	0.535	0.390	0.304	0.318	0.250	0.073	
1999–00	0.549	0.705	0.480	0.550	0.415	0.509	0.316	0.143	0.420	0.368
2000–01	0.934	0.813	0.650	0.572	0.437	0.417	0.217	0.052		
2001–02	0.461	0.561	0.528	0.544	0.872	0.478	0.251	0.176		0.692
2002–03	0.875	0.743	0.617	0.685	0.451	0.250				0.550
2003–04	1.150	0.762	0.674	0.595	0.305			0.370	0.246	0.374
2004–05	0.675	0.700	0.956	0.438	0.672	0.464	1.338	1.150		0.250
2005–06	0.408	0.779	0.814	0.688	0.561	0.366	0.161			
2006–07	0.735	0.633	0.450	0.664	0.846	0.202				
2007–08	0.613	0.696	0.366	0.608	0.328	0.325				
2008–09	0.610	0.814	0.396	0.595	0.530	0.425			0.217	
2009–10	0.963	0.729	0.653	0.356			0.329			
2010–11	0.964	0.389	0.218	0.139	0.128	0.169				
2011–12	0.489	0.502	0.426	0.228	0.260	0.229				0.028

Data source: Fisheries Victoria CandE Database (11 January 2013)

Table 12.1.1. Monthly Tweedie-standardised targeted-CPUE from 1978–79 to 2011–12 for each zone

Data: screened and selected; CPUE, catch per unit effort targeted at SRL or both SRL and GC, and Tweedie-standardised; SRL, southern rock lobster; GC, giant crab.

Fishing year	Mean Tweedie-standardised targeted-CPUE (kg per potlift) for each month									
	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug–Sep
Western Zone										
1978–79	0.841	1.059	0.997	1.013	0.906	0.741	0.680	0.671	0.476	0.589
1979–80	0.916	1.010	1.053	1.048	0.952	0.765	0.596	0.632	0.592	0.617
1980–81	1.008	1.085	1.095	1.097	0.841	0.803	0.610	0.429	0.571	0.569
1981–82	0.868	1.002	1.081	1.017	0.892	0.701	0.533	0.563	0.498	0.591
1982–83	1.004	1.144	1.039	1.038	0.865	0.755	0.541	0.443	0.603	0.529
1983–84	0.785	1.016	1.044	0.966	0.759	0.630	0.563	0.341	0.482	0.534
1984–85	0.718	0.827	0.891	0.956	0.820	0.648	0.496	0.445	0.390	0.452
1985–86	0.689	0.728	0.773	0.793	0.725	0.503	0.435	0.308	0.297	0.423
1986–87	0.656	0.684	0.685	0.716	0.733	0.601	0.428	0.402	0.431	0.441
1987–88	0.610	0.711	0.773	0.771	0.733	0.606	0.401	0.290	0.354	0.404
1988–89	0.495	0.618	0.677	0.619	0.649	0.502	0.398	0.339	0.371	0.418
1989–90	0.564	0.653	0.714	0.688	0.625	0.489	0.355	0.294	0.340	0.349
1990–91	0.507	0.588	0.639	0.651	0.583	0.455	0.365	0.272	0.321	0.312
1991–92	0.597	0.696	0.797	0.791	0.719	0.610	0.473	0.351	0.298	0.359
1992–93	0.565	0.662	0.748	0.671	0.646	0.544	0.467	0.291	0.313	0.333
1993–94	0.675	0.719	0.670	0.796	0.737	0.521	0.418	0.308	0.298	0.318
1994–95	0.552	0.729	0.740	0.652	0.582	0.457	0.369	0.284	0.259	0.297
1995–96	0.517	0.668	0.752	0.741	0.622	0.411	0.344	0.255	0.265	0.264
1996–97	0.499	0.580	0.631	0.621	0.507	0.398	0.318	0.254	0.261	0.295
1997–98	0.515	0.702	0.714	0.612	0.531	0.454	0.346	0.265	0.255	0.345
1998–99	0.620	0.723	0.694	0.662	0.635	0.519	0.370	0.259	0.295	0.361
1999–00	0.650	0.677	0.684	0.688	0.548	0.469	0.346	0.232	0.304	0.356
2000–01	0.669	0.655	0.704	0.659	0.521	0.396	0.340	0.224	0.292	0.306
2001–02	0.622	0.632	0.735	0.741	0.671	0.514	0.386	0.266	0.277	0.339
2002–03	0.678	0.751	0.756	0.706	0.649	0.589	0.430	0.252	0.293	0.355
2003–04	0.655	0.680	0.702	0.773	0.679	0.569	0.447	0.326	0.310	0.342
2004–05	0.657	0.700	0.678	0.628	0.568	0.494	0.355	0.259	0.234	0.303
2005–06	0.539	0.519	0.622	0.545	0.458	0.352	0.240	0.182	0.266	0.270
2006–07	0.441	0.498	0.502	0.568	0.472	0.382	0.262	0.208	0.229	0.288
2007–08	0.509	0.454	0.484	0.467	0.435	0.314	0.230	0.208	0.229	0.193
2008–09	0.368	0.480	0.454	0.430	0.371	0.259	0.207	0.194	0.212	0.202
2009–10	0.409	0.419	0.430	0.431	0.366	0.297	0.250	0.198	0.204	0.231
2010–11	0.454	0.415	0.527	0.466	0.415	0.347	0.267	0.221	0.331	0.292
2011–12	0.488	0.516	0.516	0.488	0.428	0.378	0.296	0.231	0.307	0.340
Eastern Zone										
1978–79	0.663	0.770	0.885	0.754	0.606	0.509	0.508	0.325	0.547	0.638
1979–80	0.719	0.772	0.777	0.762	0.589	0.589	0.436	0.139	0.575	0.597
1980–81	0.742	0.819	0.852	0.794	0.584	0.576	0.486	0.367	0.498	0.604
1981–82	0.663	0.731	0.731	0.733	0.583	0.437	0.290	0.223	0.405	0.508
1982–83	0.730	0.747	0.764	0.795	0.647	0.479	0.465	0.361	0.495	0.563
1983–84	0.616	0.708	0.801	0.770	0.585	0.551	0.422	0.429	0.368	0.484
1984–85	0.532	0.585	0.586	0.591	0.495	0.441	0.369	0.264	0.251	0.362
1985–86	0.463	0.520	0.497	0.460	0.416	0.326	0.328	0.202	0.322	0.324
1986–87	0.472	0.477	0.483	0.496	0.467	0.367	0.332	0.308	0.360	0.362
1987–88	0.379	0.436	0.514	0.385	0.424	0.297	0.280	0.362	0.252	0.269
1988–89	0.372	0.430	0.448	0.380	0.330	0.267	0.180	0.290	0.288	0.313
1989–90	0.457	0.393	0.449	0.397	0.358	0.254	0.213	0.218	0.264	0.376
1990–91	0.357	0.403	0.445	0.436	0.364	0.300	0.274	0.253	0.367	0.406
1991–92	0.414	0.354	0.386	0.464	0.393	0.340	0.270	0.230	0.206	0.291
1992–93	0.352	0.364	0.333	0.300	0.301	0.256	0.240	0.225	0.208	0.205
1993–94	0.315	0.328	0.315	0.305	0.284	0.194	0.161	0.153	0.164	0.201
1994–95	0.230	0.281	0.281	0.259	0.215	0.209	0.193	0.146	0.178	0.188
1995–96	0.253	0.280	0.277	0.295	0.239	0.183	0.171	0.182	0.169	0.154
1996–97	0.187	0.237	0.239	0.222	0.193	0.188	0.206	0.144	0.176	0.215
1997–98	0.262	0.258	0.269	0.257	0.233	0.210	0.171	0.166	0.168	0.230
1998–99	0.269	0.282	0.304	0.296	0.233	0.240	0.182	0.188	0.215	0.272
1999–00	0.267	0.289	0.317	0.332	0.257	0.206	0.202	0.180	0.193	0.284
2000–01	0.357	0.348	0.298	0.266	0.231	0.215	0.195	0.199	0.247	0.268
2001–02	0.351	0.354	0.410	0.390	0.321	0.259	0.183	0.178	0.228	0.272
2002–03	0.336	0.352	0.377	0.401	0.300	0.330	0.268	0.203	0.239	0.368
2003–04	0.424	0.447	0.413	0.394	0.364	0.281	0.246	0.274	0.268	0.353
2004–05	0.458	0.514	0.417	0.348	0.370	0.347	0.220	0.292	0.257	0.309
2005–06	0.432	0.427	0.488	0.380	0.363	0.257	0.248	0.234	0.267	0.325
2006–07	0.371	0.438	0.498	0.469	0.351	0.297	0.264	0.219	0.230	0.306
2007–08	0.392	0.412	0.408	0.359	0.344	0.306	0.184	0.199	0.301	0.312
2008–09	0.371	0.414	0.380	0.362	0.356	0.312	0.261	0.220	0.287	0.253
2009–10	0.367	0.380	0.395	0.385	0.273	0.221	0.217	0.235	0.299	0.460
2010–11	0.440	0.485	0.551	0.432	0.346	0.322	0.245	0.173	0.371	0.426
2011–12	0.523	0.605	0.521	0.407	0.359	0.436	0.453	0.269	0.501	0.530

Data source: Fisheries Victoria CandE Database (11 January 2013)

Table 12.2.1. Monthly Tweedie-standardised targeted-CPUE from 1978–79 to 2011–12 for each region

Data: screened and selected; CPUE, catch per unit effort targeted at SRL or both SRL and GC, and Tweedie-

Fishing year	Mean Tweedie-standardised targeted-CPUE (kg per potlift) for each month									
	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug–Sep
Portland Region										
1978–79	0.807	0.992	0.942	0.934	0.831	0.671	0.614	0.586	0.426	0.534
1979–80	0.876	0.943	0.992	0.963	0.871	0.691	0.536	0.551	0.528	0.558
1980–81	1.043	1.096	1.114	1.090	0.832	0.784	0.593	0.404	0.550	0.555
1981–82	0.865	0.975	1.060	0.973	0.850	0.659	0.500	0.511	0.462	0.556
1982–83	1.000	1.113	1.018	0.993	0.823	0.709	0.506	0.402	0.560	0.498
1983–84	0.730	0.922	0.954	0.862	0.674	0.553	0.492	0.289	0.418	0.469
1984–85	0.665	0.748	0.812	0.851	0.727	0.567	0.432	0.375	0.337	0.396
1985–86	0.673	0.695	0.743	0.745	0.677	0.464	0.400	0.274	0.270	0.390
1986–87	0.657	0.669	0.676	0.689	0.703	0.568	0.403	0.368	0.402	0.417
1987–88	0.558	0.634	0.696	0.677	0.641	0.523	0.344	0.241	0.302	0.349
1988–89	0.459	0.559	0.617	0.551	0.575	0.439	0.347	0.286	0.321	0.366
1989–90	0.545	0.616	0.679	0.639	0.578	0.446	0.323	0.259	0.306	0.318
1990–91	0.479	0.542	0.594	0.591	0.527	0.406	0.324	0.234	0.283	0.278
1991–92	0.572	0.651	0.751	0.729	0.660	0.552	0.427	0.307	0.266	0.325
1992–93	0.492	0.564	0.641	0.561	0.538	0.448	0.382	0.231	0.255	0.274
1993–94	0.610	0.634	0.596	0.690	0.637	0.444	0.355	0.254	0.251	0.271
1994–95	0.536	0.691	0.707	0.609	0.540	0.419	0.336	0.251	0.235	0.273
1995–96	0.487	0.614	0.697	0.670	0.560	0.366	0.305	0.219	0.233	0.234
1996–97	0.482	0.547	0.599	0.576	0.468	0.363	0.289	0.224	0.235	0.269
1997–98	0.510	0.679	0.697	0.583	0.504	0.425	0.322	0.239	0.236	0.323
1998–99	0.574	0.654	0.632	0.589	0.562	0.454	0.322	0.219	0.255	0.316
1999–00	0.626	0.637	0.648	0.636	0.505	0.426	0.314	0.204	0.273	0.324
2000–01	0.605	0.578	0.626	0.573	0.451	0.338	0.289	0.184	0.246	0.261
2001–02	0.624	0.620	0.727	0.715	0.645	0.487	0.365	0.244	0.259	0.322
2002–03	0.736	0.797	0.808	0.736	0.673	0.604	0.439	0.249	0.297	0.364
2003–04	0.690	0.701	0.729	0.783	0.684	0.567	0.443	0.313	0.305	0.341
2004–05	0.717	0.746	0.728	0.659	0.593	0.510	0.365	0.258	0.238	0.312
2005–06	0.520	0.489	0.591	0.505	0.423	0.321	0.217	0.160	0.239	0.246
2006–07	0.419	0.462	0.469	0.518	0.429	0.343	0.234	0.190	0.212	0.259
2007–08	0.478	0.417	0.448	0.421	0.391	0.279	0.203	0.190	0.212	0.171
2008–09	0.343	0.436	0.416	0.384	0.330	0.227	0.181	0.165	0.184	0.178
2009–10	0.399	0.398	0.412	0.403	0.341	0.273	0.229	0.176	0.185	0.213
2010–11	0.458	0.409	0.524	0.451	0.401	0.330	0.253	0.204	0.312	0.279
2011–12	0.458	0.474	0.478	0.441	0.384	0.336	0.262	0.198	0.269	0.302
Warrnambool Region										
1978–79	0.759	1.032	1.016	1.077	0.960	0.784	0.706	0.702	0.512	0.631
1979–80	0.830	0.987	1.078	1.119	1.013	0.812	0.621	0.664	0.638	0.663
1980–81	0.796	0.924	0.975	1.020	0.779	0.742	0.553	0.392	0.536	0.532
1981–82	0.716	0.892	1.007	0.988	0.864	0.678	0.506	0.538	0.489	0.578
1982–83	0.834	1.025	0.974	1.016	0.843	0.735	0.516	0.426	0.596	0.521
1983–84	0.763	1.066	1.145	1.106	0.866	0.718	0.629	0.385	0.558	0.616
1984–85	0.695	0.864	0.973	1.090	0.932	0.735	0.551	0.499	0.449	0.519
1985–86	0.633	0.722	0.802	0.860	0.783	0.542	0.460	0.328	0.325	0.461
1986–87	0.582	0.655	0.687	0.749	0.764	0.625	0.436	0.414	0.455	0.464
1987–88	0.579	0.728	0.828	0.862	0.817	0.674	0.437	0.319	0.400	0.454
1988–89	0.435	0.586	0.671	0.640	0.669	0.517	0.402	0.345	0.388	0.436
1989–90	0.472	0.589	0.674	0.678	0.614	0.479	0.341	0.285	0.338	0.345
1990–91	0.472	0.590	0.671	0.714	0.637	0.496	0.390	0.293	0.356	0.344
1991–92	0.548	0.690	0.827	0.857	0.777	0.657	0.500	0.374	0.326	0.391
1992–93	0.581	0.735	0.869	0.813	0.780	0.656	0.552	0.347	0.384	0.406
1993–94	0.660	0.759	0.740	0.917	0.846	0.597	0.470	0.349	0.347	0.368
1994–95	0.484	0.689	0.732	0.674	0.599	0.469	0.371	0.289	0.270	0.309
1995–96	0.477	0.665	0.784	0.806	0.675	0.445	0.365	0.273	0.291	0.289
1996–97	0.466	0.585	0.665	0.683	0.556	0.436	0.341	0.275	0.291	0.327
1997–98	0.427	0.628	0.669	0.598	0.517	0.441	0.329	0.254	0.252	0.339
1998–99	0.593	0.746	0.749	0.746	0.713	0.581	0.407	0.287	0.336	0.409
1999–00	0.567	0.637	0.674	0.706	0.561	0.480	0.347	0.235	0.315	0.368
2000–01	0.647	0.683	0.768	0.751	0.592	0.449	0.378	0.251	0.336	0.350
2001–02	0.537	0.590	0.718	0.755	0.682	0.521	0.384	0.267	0.285	0.347
2002–03	0.537	0.643	0.677	0.659	0.604	0.547	0.392	0.231	0.276	0.334
2003–04	0.572	0.641	0.693	0.795	0.696	0.583	0.448	0.330	0.323	0.354
2004–05	0.591	0.680	0.688	0.666	0.600	0.522	0.367	0.270	0.251	0.323
2005–06	0.524	0.544	0.682	0.623	0.522	0.401	0.267	0.204	0.307	0.311
2006–07	0.428	0.522	0.550	0.649	0.538	0.435	0.293	0.233	0.264	0.331
2007–08	0.515	0.496	0.553	0.556	0.516	0.372	0.267	0.233	0.264	0.231
2008–09	0.384	0.541	0.536	0.529	0.454	0.316	0.248	0.235	0.264	0.250
2009–10	0.396	0.437	0.469	0.491	0.415	0.336	0.278	0.222	0.234	0.265
2010–11	0.433	0.427	0.568	0.523	0.466	0.388	0.293	0.245	0.377	0.331
2011–12	0.544	0.621	0.650	0.641	0.560	0.495	0.380	0.299	0.408	0.450

Data source: Fisheries Victoria CandE Database (11 January 2013)

Table 12.2.2. Monthly Tweedie-standardised targeted-CPUE from 1978–79 to 2011–12 for each region

Data: screened and selected; CPUE, catch per unit effort targeted at SRL or both SRL and GC, and Tweedie-standardised; SRL, southern rock lobster; GC, giant crab.

Fishing year	Mean Tweedie-standardised targeted-CPUE (kg per potlift) for each month									
	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug–Sep
Apollo Bay Region										
1978–79	1.082	1.335	1.145	1.171	1.061	0.891	0.840	0.822	0.586	0.727
1979–80	1.183	1.277	1.215	1.217	1.120	0.923	0.740	0.779	0.731	0.765
1980–81	1.243	1.310	1.204	1.215	0.944	0.925	0.722	0.504	0.672	0.672
1981–82	1.143	1.292	1.269	1.203	1.069	0.862	0.674	0.706	0.626	0.745
1982–83	1.280	1.429	1.181	1.189	1.004	0.899	0.662	0.538	0.735	0.647
1983–84	0.985	1.248	1.168	1.088	0.866	0.739	0.678	0.408	0.578	0.642
1984–85	0.909	1.025	1.006	1.088	0.945	0.767	0.603	0.536	0.471	0.549
1985–86	0.823	0.852	0.824	0.852	0.788	0.561	0.499	0.350	0.339	0.484
1986–87	0.789	0.806	0.735	0.774	0.803	0.675	0.494	0.461	0.495	0.509
1987–88	0.815	0.929	0.921	0.925	0.891	0.756	0.514	0.369	0.452	0.517
1988–89	0.707	0.864	0.862	0.794	0.843	0.670	0.546	0.461	0.507	0.573
1989–90	0.790	0.895	0.892	0.866	0.797	0.640	0.478	0.392	0.455	0.468
1990–91	0.664	0.754	0.747	0.767	0.696	0.557	0.459	0.339	0.402	0.392
1991–92	0.749	0.855	0.893	0.893	0.822	0.715	0.571	0.420	0.358	0.432
1992–93	0.825	0.947	0.974	0.880	0.858	0.742	0.654	0.405	0.437	0.465
1993–94	0.969	1.011	0.859	1.027	0.963	0.699	0.577	0.422	0.410	0.437
1994–95	0.710	0.918	0.849	0.754	0.681	0.549	0.455	0.348	0.319	0.367
1995–96	0.699	0.885	0.908	0.901	0.766	0.520	0.447	0.329	0.343	0.342
1996–97	0.607	0.690	0.683	0.678	0.560	0.452	0.371	0.294	0.304	0.344
1997–98	0.643	0.859	0.797	0.687	0.605	0.530	0.415	0.315	0.305	0.413
1998–99	0.828	0.947	0.827	0.795	0.772	0.648	0.475	0.330	0.377	0.462
1999–00	0.868	0.885	0.814	0.824	0.665	0.585	0.444	0.295	0.387	0.456
2000–01	0.954	0.914	0.895	0.845	0.677	0.527	0.466	0.304	0.398	0.418
2001–02	0.765	0.762	0.808	0.820	0.752	0.591	0.457	0.312	0.326	0.400
2002–03	0.768	0.834	0.765	0.719	0.669	0.624	0.468	0.272	0.317	0.386
2003–04	0.713	0.726	0.683	0.756	0.673	0.580	0.467	0.339	0.323	0.357
2004–05	0.622	0.649	0.573	0.534	0.490	0.438	0.323	0.234	0.212	0.275
2005–06	0.609	0.574	0.627	0.553	0.471	0.372	0.260	0.196	0.287	0.292
2006–07	0.532	0.589	0.540	0.616	0.519	0.431	0.304	0.212	0.236	0.333
2007–08	0.588	0.514	0.499	0.485	0.457	0.339	0.255	0.212	0.236	0.214
2008–09	0.419	0.535	0.461	0.440	0.384	0.275	0.226	0.211	0.231	0.220
2009–10	0.450	0.451	0.422	0.426	0.366	0.305	0.264	0.208	0.214	0.244
2010–11	0.459	0.412	0.477	0.424	0.383	0.328	0.259	0.214	0.321	0.284
2011–12	0.521	0.540	0.492	0.469	0.416	0.378	0.304	0.236	0.314	0.348
Queenscliff Region										
1978–79	0.663	0.734	0.857	0.731	0.559	0.455	0.468	0.269	0.491	0.639
1979–80	0.741	0.759	0.775	0.762	0.560	0.543	0.415	0.119	0.533	0.617
1980–81	0.756	0.796	0.840	0.784	0.549	0.525	0.457	0.310	0.456	0.616
1981–82	0.636	0.669	0.678	0.682	0.516	0.375	0.257	0.177	0.349	0.488
1982–83	0.715	0.698	0.724	0.755	0.584	0.419	0.420	0.293	0.435	0.552
1983–84	0.646	0.709	0.813	0.783	0.566	0.517	0.408	0.373	0.347	0.508
1984–85	0.533	0.559	0.568	0.573	0.457	0.394	0.341	0.219	0.225	0.363
1985–86	0.476	0.511	0.495	0.459	0.395	0.300	0.311	0.172	0.298	0.334
1986–87	0.495	0.477	0.490	0.504	0.452	0.344	0.321	0.267	0.339	0.380
1987–88	0.390	0.427	0.512	0.383	0.402	0.273	0.265	0.308	0.233	0.277
1988–89	0.403	0.445	0.471	0.400	0.331	0.259	0.180	0.261	0.280	0.340
1989–90	0.524	0.429	0.498	0.441	0.378	0.260	0.225	0.207	0.272	0.432
1990–91	0.374	0.402	0.451	0.442	0.351	0.280	0.265	0.219	0.345	0.426
1991–92	0.425	0.346	0.384	0.461	0.372	0.312	0.255	0.195	0.190	0.299
1992–93	0.353	0.349	0.324	0.292	0.278	0.230	0.222	0.187	0.188	0.206
1993–94	0.319	0.316	0.308	0.299	0.265	0.175	0.150	0.128	0.149	0.203
1994–95	0.227	0.265	0.269	0.248	0.196	0.185	0.176	0.120	0.158	0.186
1995–96	0.259	0.273	0.274	0.292	0.225	0.167	0.161	0.154	0.155	0.158
1996–97	0.174	0.210	0.215	0.200	0.165	0.156	0.176	0.111	0.146	0.200
1997–98	0.257	0.241	0.255	0.244	0.211	0.184	0.155	0.134	0.148	0.226
1998–99	0.288	0.287	0.315	0.307	0.230	0.230	0.180	0.167	0.206	0.292
1999–00	0.310	0.321	0.357	0.374	0.275	0.214	0.216	0.174	0.202	0.331
2000–01	0.399	0.371	0.323	0.288	0.238	0.215	0.201	0.184	0.248	0.301
2001–02	0.371	0.358	0.420	0.400	0.313	0.245	0.178	0.156	0.217	0.288
2002–03	0.377	0.377	0.409	0.436	0.311	0.331	0.278	0.188	0.241	0.414
2003–04	0.459	0.461	0.432	0.414	0.363	0.272	0.246	0.246	0.261	0.383
2004–05	0.476	0.510	0.420	0.351	0.355	0.322	0.211	0.251	0.239	0.322
2005–06	0.437	0.412	0.478	0.372	0.338	0.232	0.231	0.196	0.242	0.329
2006–07	0.378	0.425	0.491	0.463	0.330	0.271	0.248	0.185	0.211	0.313
2007–08	0.409	0.410	0.412	0.363	0.331	0.286	0.177	0.172	0.282	0.326
2008–09	0.383	0.408	0.379	0.362	0.338	0.288	0.248	0.188	0.266	0.262
2009–10	0.369	0.364	0.384	0.375	0.253	0.199	0.201	0.196	0.270	0.463
2010–11	0.444	0.467	0.539	0.423	0.322	0.291	0.228	0.145	0.337	0.432
2011–12	0.553	0.611	0.533	0.417	0.350	0.412	0.442	0.236	0.476	0.561

Data source: Fisheries Victoria CandE Database (11 January 2013)

Table 12.2.3. Monthly Tweedie-standardised targeted-CPUE from 1978–79 to 2011–12 for each region

Data: screened and selected; CPUE, catch per unit effort targeted at SRL or both SRL and GC, and Tweedie-standardised; SRL, southern rock lobster; GC, giant crab.

Fishing year	Mean Tweedie-standardised targeted-CPUE (kg per potlift) for each month									
	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug–Sep
San Remo Region										
1978–79	0.625	0.831	0.936	0.777	0.664	0.550	0.526	0.348	0.676	0.608
1979–80	0.637	0.785	0.773	0.739	0.608	0.599	0.425	0.140	0.670	0.536
1980–81	0.685	0.867	0.883	0.802	0.628	0.610	0.493	0.386	0.605	0.565
1981–82	0.700	0.884	0.865	0.846	0.717	0.529	0.337	0.267	0.561	0.542
1982–83	0.728	0.855	0.855	0.867	0.751	0.548	0.510	0.410	0.649	0.568
1983–84	0.543	0.716	0.794	0.743	0.601	0.558	0.409	0.431	0.427	0.432
1984–85	0.502	0.633	0.621	0.609	0.544	0.477	0.383	0.284	0.311	0.345
1985–86	0.417	0.538	0.503	0.454	0.437	0.337	0.325	0.207	0.382	0.296
1986–87	0.403	0.467	0.463	0.464	0.465	0.359	0.312	0.299	0.405	0.313
1987–88	0.343	0.452	0.522	0.381	0.446	0.309	0.278	0.373	0.300	0.246
1988–89	0.317	0.420	0.429	0.354	0.328	0.261	0.169	0.281	0.322	0.270
1989–90	0.350	0.344	0.386	0.332	0.319	0.223	0.179	0.190	0.266	0.291
1990–91	0.315	0.408	0.441	0.421	0.374	0.304	0.266	0.254	0.426	0.363
1991–92	0.361	0.354	0.378	0.442	0.400	0.340	0.258	0.228	0.236	0.257
1992–93	0.335	0.398	0.356	0.313	0.334	0.280	0.251	0.244	0.261	0.198
1993–94	0.295	0.352	0.331	0.313	0.310	0.208	0.166	0.163	0.202	0.190
1994–95	0.215	0.302	0.295	0.265	0.235	0.225	0.198	0.156	0.219	0.178
1995–96	0.220	0.279	0.270	0.280	0.242	0.182	0.164	0.180	0.193	0.136
1996–97	0.188	0.273	0.269	0.244	0.226	0.217	0.227	0.165	0.232	0.218
1997–98	0.254	0.287	0.294	0.273	0.264	0.234	0.182	0.183	0.214	0.226
1998–99	0.232	0.279	0.295	0.280	0.234	0.238	0.173	0.185	0.244	0.238
1999–00	0.211	0.262	0.281	0.287	0.236	0.187	0.175	0.162	0.201	0.227
2000–01	0.274	0.306	0.257	0.223	0.207	0.190	0.165	0.174	0.249	0.209
2001–02	0.306	0.355	0.402	0.372	0.326	0.260	0.175	0.177	0.262	0.240
2002–03	0.249	0.300	0.314	0.325	0.259	0.281	0.219	0.171	0.233	0.276
2003–04	0.341	0.412	0.372	0.347	0.340	0.259	0.217	0.251	0.283	0.287
2004–05	0.417	0.537	0.427	0.347	0.393	0.362	0.220	0.303	0.307	0.285
2005–06	0.412	0.467	0.523	0.396	0.403	0.281	0.259	0.254	0.334	0.314
2006–07	0.344	0.465	0.517	0.475	0.378	0.315	0.268	0.231	0.280	0.287
2007–08	0.344	0.415	0.402	0.345	0.352	0.308	0.178	0.199	0.347	0.278
2008–09	0.338	0.432	0.388	0.360	0.377	0.326	0.261	0.228	0.343	0.233
2009–10	0.349	0.413	0.421	0.400	0.302	0.241	0.226	0.254	0.373	0.442
2010–11	0.418	0.529	0.589	0.450	0.383	0.351	0.256	0.188	0.465	0.411
2011–12	0.460	0.612	0.515	0.392	0.368	0.440	0.438	0.270	0.580	0.473
Lakes Entrance Region										
1978–79	1.094	1.131	1.146	0.997	0.816	0.717	0.466	0.330	0.565	0.630
1979–80	0.916	0.876	0.777	0.778	0.613	0.641	0.309	0.109	0.459	0.456
1980–81	0.991	0.975	0.894	0.850	0.637	0.657	0.362	0.302	0.418	0.483
1981–82	0.687	0.675	0.594	0.609	0.493	0.387	0.167	0.142	0.263	0.315
1982–83	0.760	0.694	0.625	0.663	0.550	0.426	0.270	0.232	0.323	0.351
1983–84	0.699	0.716	0.714	0.700	0.542	0.534	0.266	0.300	0.262	0.329
1984–85	0.843	0.826	0.729	0.750	0.641	0.596	0.326	0.258	0.249	0.343
1985–86	0.736	0.738	0.621	0.587	0.541	0.443	0.290	0.198	0.322	0.309
1986–87	0.856	0.771	0.688	0.722	0.693	0.568	0.336	0.345	0.410	0.393
1987–88	0.571	0.585	0.608	0.465	0.521	0.382	0.235	0.336	0.238	0.242
1988–89	0.531	0.547	0.502	0.435	0.385	0.326	0.143	0.255	0.258	0.267
1989–90	0.550	0.421	0.424	0.382	0.351	0.261	0.142	0.162	0.199	0.271
1990–91	0.460	0.462	0.450	0.449	0.383	0.330	0.196	0.201	0.297	0.313
1991–92	0.653	0.497	0.479	0.586	0.507	0.458	0.237	0.223	0.204	0.275
1992–93	0.503	0.465	0.374	0.344	0.351	0.313	0.191	0.199	0.187	0.176
1993–94	0.451	0.418	0.354	0.350	0.332	0.237	0.128	0.135	0.147	0.172
1994–95	0.427	0.465	0.410	0.385	0.326	0.332	0.199	0.167	0.207	0.209
1995–96	0.458	0.452	0.393	0.427	0.354	0.282	0.172	0.202	0.192	0.167
1996–97	0.445	0.502	0.445	0.423	0.374	0.382	0.272	0.211	0.262	0.305
1997–98	0.428	0.375	0.345	0.337	0.312	0.294	0.155	0.167	0.172	0.225
1998–99	0.413	0.385	0.367	0.364	0.292	0.315	0.156	0.178	0.207	0.250
1999–00	0.334	0.323	0.311	0.333	0.263	0.220	0.141	0.139	0.152	0.213
2000–01	0.496	0.431	0.325	0.296	0.262	0.256	0.151	0.170	0.215	0.223
2001–02	0.368	0.332	0.338	0.328	0.275	0.232	0.107	0.115	0.150	0.171
2002–03	0.467	0.437	0.411	0.447	0.341	0.392	0.208	0.174	0.208	0.306
2003–04	0.456	0.429	0.349	0.340	0.320	0.259	0.147	0.182	0.181	0.228
2004–05	0.515	0.516	0.369	0.314	0.340	0.333	0.138	0.203	0.181	0.208
2005–06	0.494	0.435	0.438	0.348	0.339	0.250	0.157	0.165	0.191	0.222
2006–07	0.433	0.454	0.455	0.438	0.334	0.296	0.171	0.157	0.168	0.213
2007–08	0.257	0.241	0.210	0.189	0.184	0.171	0.067	0.080	0.124	0.122
2008–09	0.474	0.472	0.381	0.371	0.371	0.340	0.185	0.173	0.230	0.194
2009–10	0.378	0.348	0.319	0.318	0.230	0.194	0.124	0.149	0.193	0.283
2010–11	0.249	0.245	0.245	0.196	0.160	0.156	0.077	0.061	0.132	0.145
2011–12	0.403	0.416	0.315	0.251	0.226	0.287	0.194	0.128	0.242	0.244

Data source: Fisheries Victoria CandE Database (11 January 2013)

Table 13. Catch mass and catch number during fishing years from 1978–79 to 2011–12 for each region by zone

Data: non-screened and non-selected; fishing year, Nov–Sep.

Fishing year	Catch mass (tonne) for each region				Catch number ('000) for each region			
	Portland	Warrnambool	Apollo Bay	Total	Portland	Warrnambool	Apollo Bay	Total
Western Zone								
1978–79	236	136	114	486	242	130	112	485
1979–80	216	125	111	453	218	118	107	444
1980–81	325	112	112	549	325	112	111	548
1981–82	264	111	123	499	266	110	124	499
1982–83	254	91	115	460	250	87	117	455
1983–84	200	122	98	421	203	114	97	414
1984–85	187	114	105	406	189	105	100	394
1985–86	171	85	89	345	179	81	87	346
1986–87	180	85	86	351	188	81	84	353
1987–88	182	90	73	345	188	87	74	349
1988–89	162	68	75	304	180	68	74	322
1989–90	193	63	75	331	213	65	77	355
1990–91	185	68	64	317	201	70	66	337
1991–92	246	93	69	408	273	95	72	439
1992–93	215	108	85	408	237	108	88	433
1993–94	235	100	114	448	246	99	111	456
1994–95	249	87	99	435	265	85	94	444
1995–96	262	83	78	423	287	79	76	442
1996–97	230	87	85	402	251	84	79	414
1997–98	271	88	107	466	303	87	102	492
1998–99	256	160	100	516	298	166	103	568
1999–00	285	129	107	521	340	139	114	592
2000–01	278	136	111	525	331	148	120	598
2001–02	231	110	97	438	277	125	108	510
2002–03	239	101	90	430	281	114	100	495
2003–04	267	100	94	461	299	110	106	515
2004–05	229	109	70	408	259	115	77	451
2005–06	201	105	52	358	237	113	56	405
2006–07	187	86	62	336	229	95	68	392
2007–08	153	80	56	289	188	90	61	338
2008–09	111	75	49	235	134	83	51	268
2009–10	120	72	47	239	146	80	51	277
2010–11	148	60	46	254	184	69	54	307
2011–12	128	58	47	233	157	67	55	279

Fishing year	Catch mass (tonne) for each region				Catch number (thousands) for each region			
	Queenscliff	San Remo	Lakes Entrance	Total	Queenscliff	San Remo	Lakes Entrance	Total
Eastern Zone								
1978–79	65	42	32	139	64	32	28	123
1979–80	61	37	18	116	64	30	15	108
1980–81	67	47	19	133	69	37	17	123
1981–82	60	53	18	131	64	40	16	120
1982–83	70	61	12	143	72	49	10	132
1983–84	84	41	12	136	85	34	9	128
1984–85	54	40	19	113	49	31	16	96
1985–86	46	31	18	95	42	24	15	81
1986–87	39	27	12	78	37	21	9	66
1987–88	40	19	12	70	37	15	10	62
1988–89	35	16	13	64	35	13	12	60
1989–90	54	19	11	83	58	16	10	85
1990–91	45	17	9	72	48	15	8	72
1991–92	44	15	6	65	46	13	5	64
1992–93	37	25	8	69	38	20	6	63
1993–94	40	31	7	79	39	22	7	68
1994–95	31	28	13	72	28	20	10	58
1995–96	33	18	6	57	29	13	6	48
1996–97	27	20	12	60	24	14	10	48
1997–98	28	26	12	66	26	18	9	54
1998–99	33	24	10	67	32	18	8	58
1999–00	44	23	7	75	48	17	6	71
2000–01	43	20	10	73	44	15	8	67
2001–02	33	16	4	53	34	12	3	50
2002–03	34	13	5	52	34	10	4	48
2003–04	39	14	3	56	39	10	2	51
2004–05	37	13	4	55	36	9	3	49
2005–06	28	23	2	52	27	17	2	46
2006–07	31	21	2	54	30	16	2	48
2007–08	24	21	2	46	23	15	1	39
2008–09	21	17	1	39	19	12	1	32
2009–10	32	22	1	55	32	17	1	50
2010–11	35	28	3	66	39	22	2	62
2011–12	35	25	2	62	36	18	1	55

Data source: Fisheries Victoria CandE Database (11 January 2013)

Table 14. Nominal fishing effort and ratio nominal-targeted-CPUE during fishing years from 1978–79 to 2011–12 for each region by zone

Data: non-screened and non-selected; fishing year, Nov–Sep; nominal fishing effort is effort as reported on mandatory logbook returns; Ratio nominal-targeted-CPUE is total catch/total nominal effort targeted at SRL or at both SRL & GC.

Fishing year	Nominal fishing effort ('000 potlifts) for each region				Ratio nominal-targeted-CPUE (kg per potlift) for each region			
	Portland	Warrnambool	Apollo Bay	Total	Portland	Warrnambool	Apollo Bay	Total
Western Zone								
1978–79	347	187	87	622	0.679	0.724	1.315	0.781
1979–80	326	165	85	576	0.664	0.760	1.299	0.786
1980–81	414	170	96	680	0.784	0.658	1.173	0.807
1981–82	352	166	119	637	0.751	0.672	1.030	0.782
1982–83	366	139	103	608	0.695	0.660	1.112	0.758
1983–84	305	164	101	571	0.656	0.746	0.967	0.737
1984–85	294	166	118	578	0.635	0.685	0.889	0.702
1985–86	292	165	112	569	0.585	0.515	0.799	0.607
1986–87	311	169	115	595	0.580	0.505	0.745	0.591
1987–88	298	163	96	557	0.613	0.554	0.755	0.620
1988–89	318	158	102	577	0.509	0.430	0.734	0.527
1989–90	367	141	105	613	0.525	0.447	0.719	0.541
1990–91	408	148	94	650	0.453	0.461	0.676	0.487
1991–92	446	172	94	712	0.552	0.543	0.734	0.574
1992–93	478	199	103	779	0.449	0.543	0.831	0.524
1993–94	455	167	132	754	0.515	0.597	0.865	0.594
1994–95	494	169	126	789	0.504	0.519	0.783	0.552
1995–96	514	137	109	761	0.510	0.601	0.711	0.556
1996–97	497	157	133	787	0.462	0.557	0.639	0.511
1997–98	513	184	145	841	0.529	0.480	0.738	0.554
1998–99	479	244	138	861	0.534	0.657	0.721	0.599
1999–00	534	223	140	897	0.534	0.579	0.759	0.581
2000–01	526	227	142	895	0.529	0.596	0.784	0.586
2001–02	385	198	121	704	0.601	0.554	0.803	0.623
2002–03	337	191	102	630	0.709	0.532	0.874	0.682
2003–04	365	181	113	659	0.731	0.551	0.835	0.699
2004–05	348	214	105	667	0.659	0.511	0.663	0.612
2005–06	416	209	80	705	0.484	0.500	0.649	0.507
2006–07	428	172	97	698	0.437	0.502	0.641	0.482
2007–08	386	174	109	668	0.397	0.460	0.511	0.432
2008–09	329	171	105	606	0.336	0.438	0.470	0.388
2009–10	353	192	106	650	0.342	0.373	0.441	0.367
2010–11	360	132	98	590	0.410	0.457	0.474	0.431
2011–12	293	97	84	475	0.436	0.594	0.555	0.490

Fishing year	Nominal fishing effort ('000 potlifts) for each region				Ratio nominal-targeted-CPUE (kg per potlift) for each region			
	Queenscliff	San Remo	Lakes Entrance	Total	Queenscliff	San Remo	Lakes Entrance	Total
Eastern Zone								
1978–79	97	68	27	192	0.668	0.624	1.176	0.724
1979–80	95	61	15	171	0.642	0.601	1.176	0.674
1980–81	98	68	14	180	0.686	0.698	1.345	0.742
1981–82	109	70	14	193	0.554	0.748	1.248	0.677
1982–83	120	85	7	212	0.586	0.717	1.698	0.675
1983–84	144	77	8	230	0.580	0.531	1.384	0.593
1984–85	111	77	12	201	0.488	0.519	1.509	0.563
1985–86	101	61	12	175	0.449	0.505	1.479	0.541
1986–87	86	52	7	145	0.457	0.517	1.565	0.535
1987–88	79	43	8	130	0.501	0.437	1.456	0.539
1988–89	84	48	13	145	0.408	0.327	1.072	0.439
1989–90	124	61	13	198	0.437	0.305	0.834	0.422
1990–91	113	50	9	172	0.400	0.343	0.988	0.415
1991–92	122	46	8	175	0.359	0.326	0.784	0.369
1992–93	133	80	12	224	0.275	0.316	0.650	0.310
1993–94	147	101	12	260	0.275	0.306	0.607	0.303
1994–95	131	100	22	253	0.236	0.283	0.590	0.285
1995–96	139	68	12	220	0.235	0.262	0.497	0.258
1996–97	125	79	19	222	0.218	0.258	0.651	0.269
1997–98	112	92	17	221	0.255	0.286	0.666	0.300
1998–99	112	90	17	220	0.295	0.269	0.567	0.306
1999–00	129	88	15	232	0.344	0.259	0.497	0.322
2000–01	131	71	17	219	0.328	0.280	0.582	0.331
2001–02	97	47	7	151	0.343	0.345	0.566	0.354
2002–03	88	39	7	134	0.388	0.335	0.761	0.391
2003–04	93	34	5	133	0.413	0.402	0.671	0.419
2004–05	95	36	5	136	0.392	0.376	0.756	0.402
2005–06	73	46	3	122	0.377	0.487	0.753	0.427
2006–07	81	50	4	136	0.378	0.414	0.567	0.397
2007–08	68	52	4	123	0.348	0.398	0.521	0.374
2008–09	61	45	2	108	0.347	0.380	0.664	0.366
2009–10	87	57	2	146	0.364	0.389	0.686	0.378
2010–11	81	57	13	150	0.438	0.487	0.204	0.437
2011–12	70	40	4	114	0.502	0.625	0.426	0.542

Data source: Fisheries Victoria CandE Database (11 January 2013)

Table 15. Mean nominal-targeted-CPUE and Tweedie-standardised targeted-CPUE during fishing years from 1978–79 to 2011–12 for each region by zone

Data screened and selected; fishing year, November–September; mean nominal-targeted-CPUE is targeted at SRL or at both SRL & GC; Tweedie-standardised targeted-CPUE is targeted at SRL or at both SRL & GC; SRL, southern rock lobster; GC, giant crab.

Fishing year	Mean nominal-targeted-CPUE (kg per potlift) for each region				Tweedie-standardised targeted-CPUE (kg per potlift) for each region			
	Portland	Warrnambool	Apollo Bay	Total	Portland	Warrnambool	Apollo Bay	Total
Western Zone								
1978–79	0.697	0.725	1.247	0.805	0.757	0.848	0.992	0.822
1979–80	0.632	0.763	1.259	0.786	0.781	0.881	1.031	0.851
1980–81	0.751	0.658	1.178	0.807	0.852	0.774	0.993	0.858
1981–82	0.711	0.678	1.051	0.775	0.780	0.769	1.007	0.815
1982–83	0.696	0.692	1.074	0.768	0.795	0.790	0.995	0.832
1983–84	0.664	0.777	0.968	0.757	0.673	0.838	0.888	0.754
1984–85	0.630	0.698	0.901	0.710	0.619	0.770	0.827	0.696
1985–86	0.606	0.548	0.813	0.632	0.568	0.636	0.679	0.605
1986–87	0.594	0.548	0.761	0.614	0.578	0.610	0.679	0.601
1987–88	0.642	0.530	0.728	0.625	0.527	0.652	0.753	0.601
1988–89	0.534	0.423	0.711	0.539	0.472	0.533	0.712	0.531
1989–90	0.541	0.441	0.702	0.550	0.494	0.509	0.701	0.533
1990–91	0.462	0.444	0.651	0.490	0.444	0.521	0.603	0.490
1991–92	0.555	0.524	0.702	0.571	0.546	0.623	0.699	0.593
1992–93	0.453	0.537	0.807	0.530	0.457	0.642	0.748	0.546
1993–94	0.518	0.568	0.851	0.594	0.485	0.625	0.753	0.559
1994–95	0.511	0.498	0.768	0.555	0.468	0.503	0.606	0.502
1995–96	0.518	0.571	0.720	0.561	0.445	0.520	0.626	0.493
1996–97	0.481	0.528	0.623	0.517	0.415	0.478	0.511	0.448
1997–98	0.546	0.470	0.749	0.569	0.464	0.462	0.573	0.488
1998–99	0.541	0.645	0.737	0.605	0.471	0.579	0.665	0.530
1999–00	0.538	0.573	0.777	0.590	0.470	0.507	0.636	0.508
2000–01	0.548	0.590	0.799	0.605	0.423	0.538	0.652	0.487
2001–02	0.623	0.569	0.840	0.656	0.517	0.530	0.619	0.536
2002–03	0.726	0.571	0.922	0.723	0.588	0.511	0.600	0.564
2003–04	0.737	0.554	0.848	0.714	0.567	0.559	0.573	0.560
2004–05	0.674	0.507	0.672	0.623	0.513	0.504	0.435	0.490
2005–06	0.482	0.519	0.656	0.525	0.381	0.456	0.435	0.411
2006–07	0.441	0.515	0.688	0.513	0.374	0.455	0.464	0.410
2007–08	0.403	0.466	0.564	0.455	0.323	0.414	0.388	0.358
2008–09	0.347	0.443	0.510	0.413	0.291	0.388	0.348	0.325
2009–10	0.335	0.395	0.454	0.378	0.310	0.366	0.342	0.331
2010–11	0.402	0.478	0.488	0.437	0.377	0.425	0.370	0.389
2011–12	0.420	0.596	0.576	0.494	0.384	0.543	0.427	0.426

Fishing year	Mean nominal-targeted-CPUE (kg per potlift) for each region				Tweedie-standardised targeted-CPUE (kg per potlift) for each region			
	Queenscliff	San Remo	Lakes Entrance	Total	Queenscliff	San Remo	Lakes Entrance	Total
Eastern Zone								
1978–79	0.655	0.620	1.177	0.696	0.633	0.702	0.834	0.663
1979–80	0.643	0.608	1.258	0.676	0.643	0.651	0.634	0.652
1980–81	0.653	0.697	1.378	0.713	0.656	0.699	0.686	0.673
1981–82	0.532	0.748	1.394	0.647	0.535	0.693	0.461	0.584
1982–83	0.649	0.721	1.887	0.710	0.603	0.723	0.511	0.644
1983–84	0.575	0.535	1.466	0.589	0.596	0.590	0.514	0.594
1984–85	0.525	0.541	1.830	0.586	0.456	0.506	0.577	0.477
1985–86	0.500	0.504	1.499	0.564	0.403	0.416	0.498	0.410
1986–87	0.481	0.496	1.596	0.540	0.429	0.412	0.592	0.428
1987–88	0.517	0.417	1.514	0.555	0.363	0.376	0.424	0.369
1988–89	0.451	0.321	1.180	0.475	0.357	0.330	0.375	0.344
1989–90	0.440	0.303	0.964	0.436	0.391	0.307	0.327	0.357
1990–91	0.405	0.354	1.057	0.435	0.381	0.379	0.374	0.381
1991–92	0.354	0.324	0.722	0.368	0.338	0.339	0.415	0.345
1992–93	0.281	0.328	0.642	0.315	0.271	0.303	0.308	0.282
1993–94	0.293	0.312	0.566	0.313	0.246	0.269	0.278	0.255
1994–95	0.259	0.294	0.543	0.299	0.217	0.241	0.324	0.229
1995–96	0.272	0.270	0.540	0.286	0.219	0.220	0.310	0.225
1996–97	0.266	0.263	0.681	0.300	0.188	0.240	0.385	0.212
1997–98	0.292	0.293	0.614	0.317	0.217	0.254	0.289	0.232
1998–99	0.329	0.270	0.549	0.328	0.269	0.256	0.308	0.263
1999–00	0.350	0.269	0.523	0.336	0.300	0.240	0.257	0.269
2000–01	0.323	0.310	0.646	0.342	0.295	0.238	0.292	0.276
2001–02	0.366	0.334	0.585	0.369	0.310	0.302	0.246	0.307
2002–03	0.409	0.330	0.703	0.406	0.354	0.276	0.350	0.330
2003–04	0.415	0.393	0.632	0.421	0.375	0.327	0.297	0.362
2004–05	0.400	0.402	0.708	0.419	0.359	0.371	0.310	0.361
2005–06	0.380	0.487	0.683	0.428	0.349	0.387	0.314	0.361
2006–07	0.376	0.435	0.528	0.402	0.359	0.384	0.327	0.368
2007–08	0.353	0.402	0.587	0.379	0.345	0.341	0.173	0.345
2008–09	0.330	0.404	0.558	0.364	0.327	0.339	0.323	0.331
2009–10	0.362	0.421	0.706	0.388	0.337	0.374	0.275	0.350
2010–11	0.454	0.475	0.284	0.453	0.401	0.445	0.180	0.415
2011–12	0.486	0.586	0.394	0.512	0.496	0.487	0.289	0.491

Data source: Fisheries Victoria CandE Database (11 January 2013)

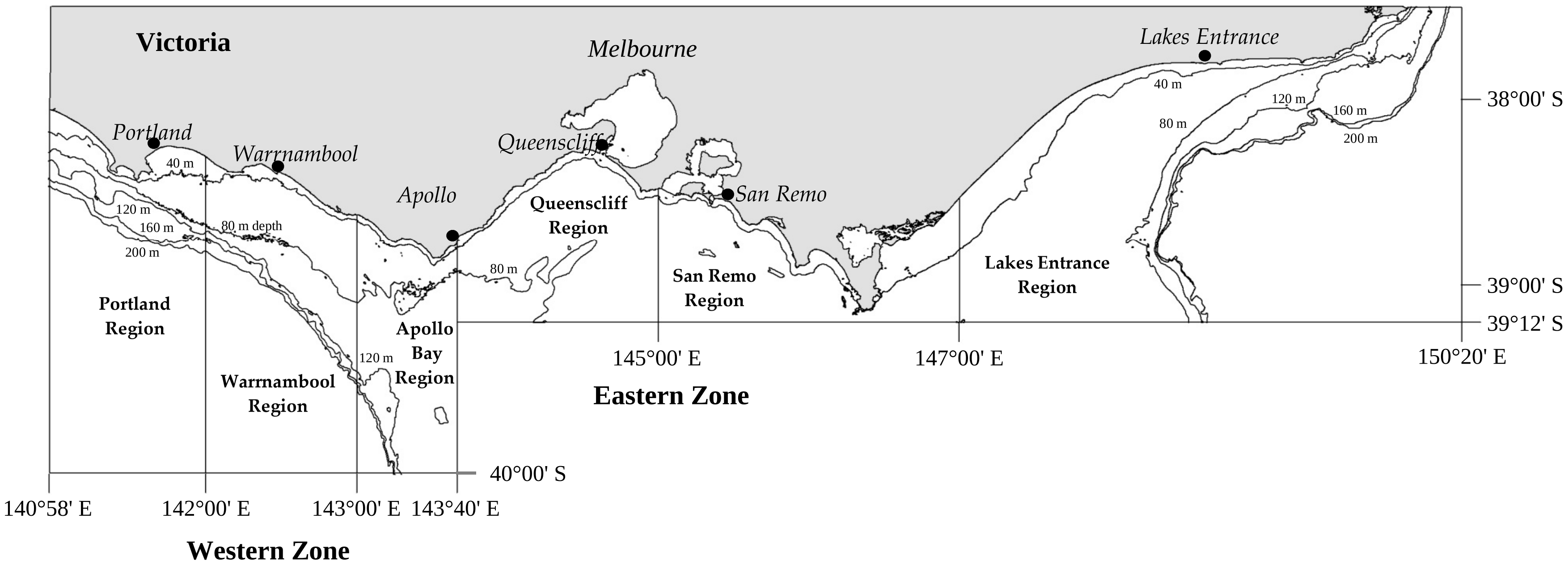


Figure 1a. Regions of Western Zone and Eastern Zone in Victoria

Western Zone is divided at longitudes 142°00' E and 143°00' E into Portland Region, Warrnambool Region, and Apollo Bay Region, and Eastern Zone is divided at longitudes 145°00' E and 147°00' E into Queenscliff Region, San Remo Region and Lakes Entrance Region where each region is named after its largest fishing

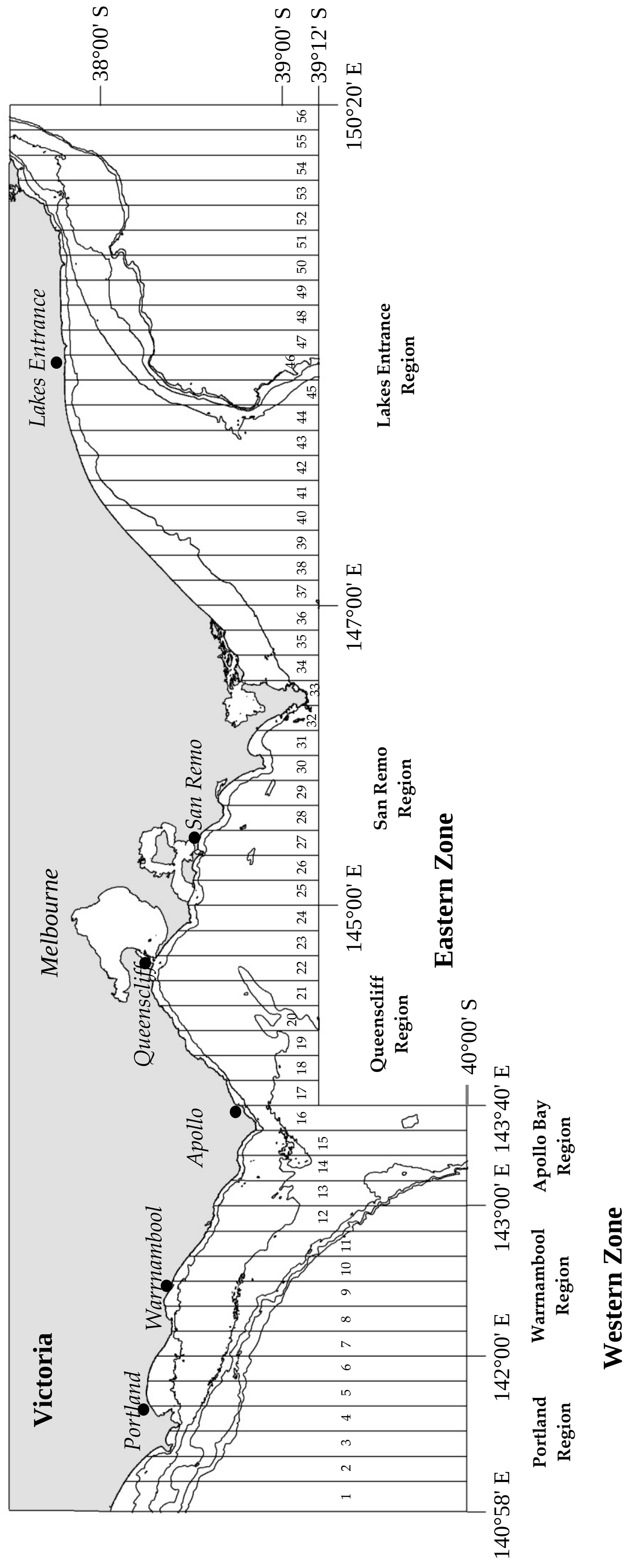


Figure 1b. Grid cells of 10-minutes of longitude in Western Zone and Eastern Zone of Victoria

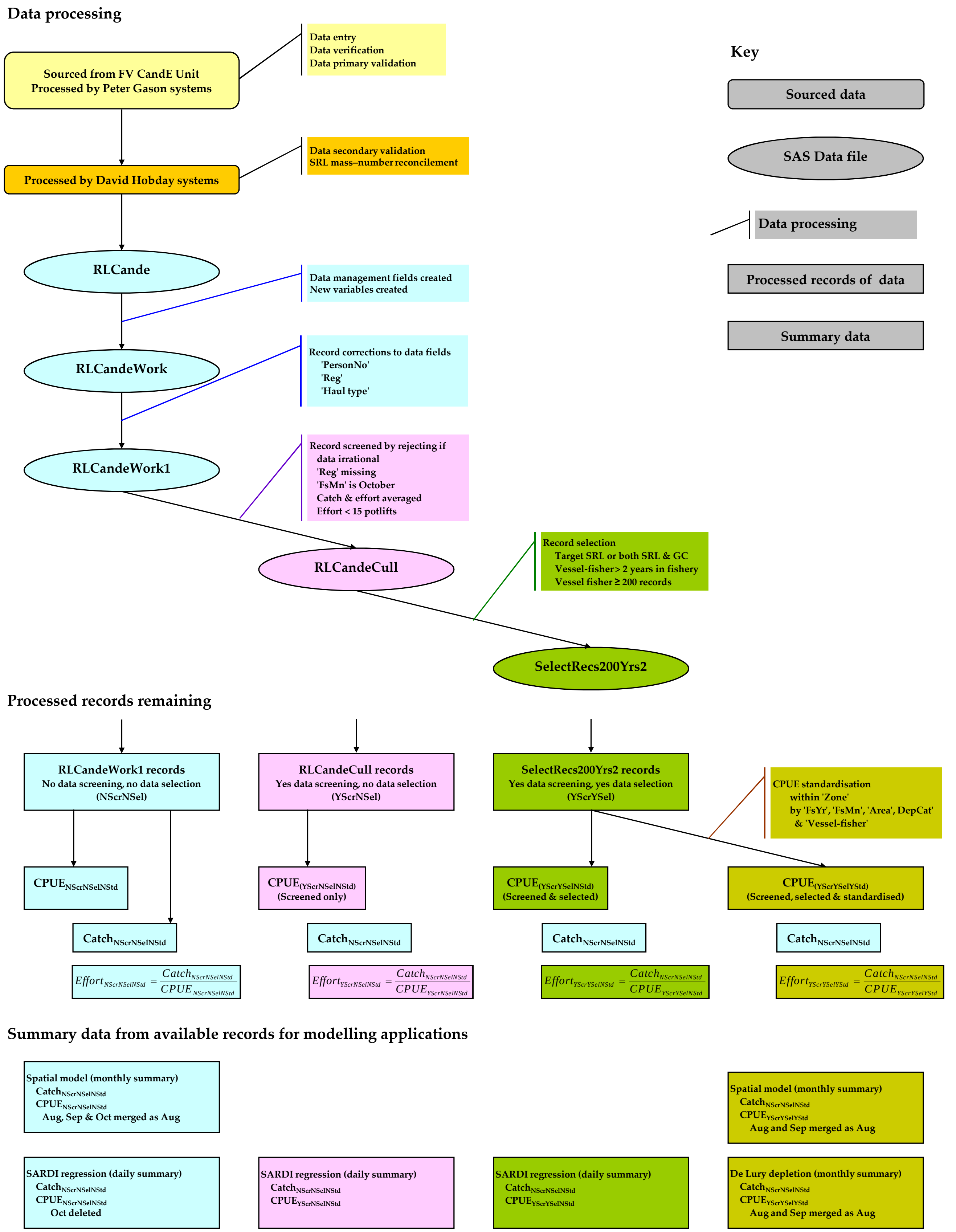
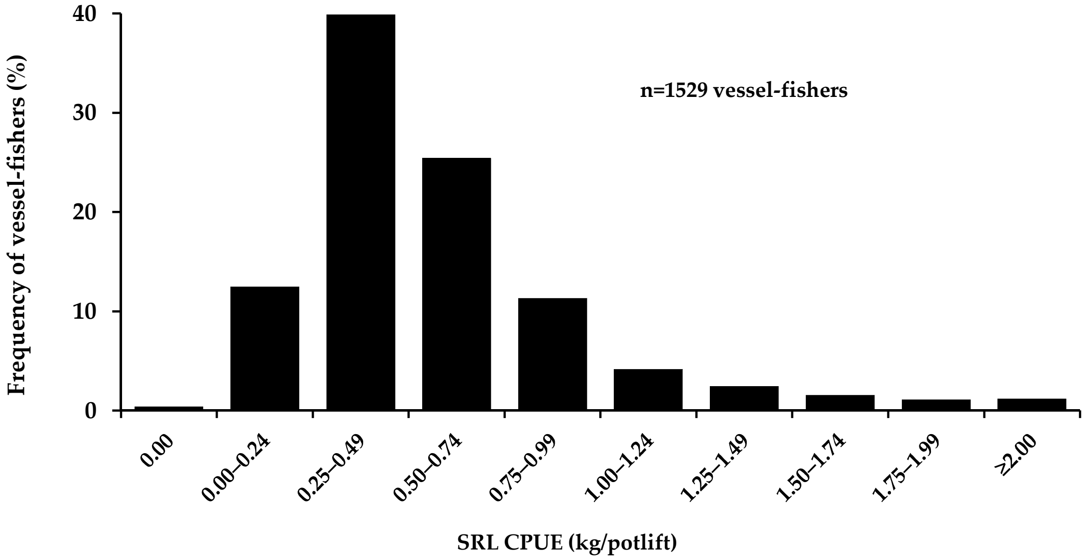
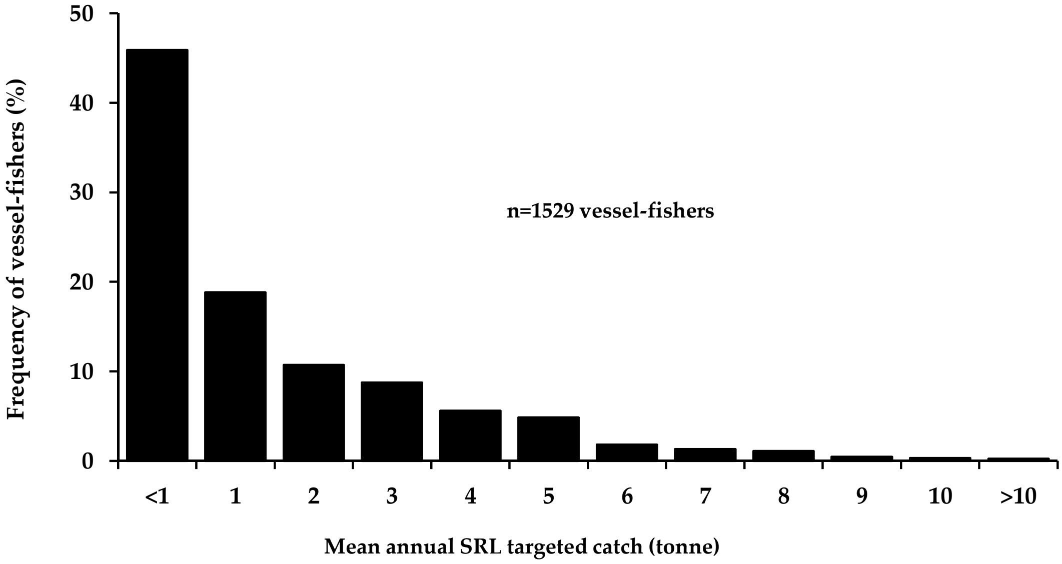


Figure 2. SAS catch and effort data files and data processing by screening, selecting, and standardising CPUE

FV, Fisheries Victoria; RL, rock lobster; CandE, catch and effort; PersonNo, fisher code; Reg, vessel registration; NScr, no data screening; YScr, yes data screening; NSel, no data selection; YSel, yes data selection; NStd, no CPUE standardisation; YStd, yes CPUE standardisation; FsMn, fishing month.



(a) Vessel-fisher performance as mean SRL-targeted nominal-CPUE



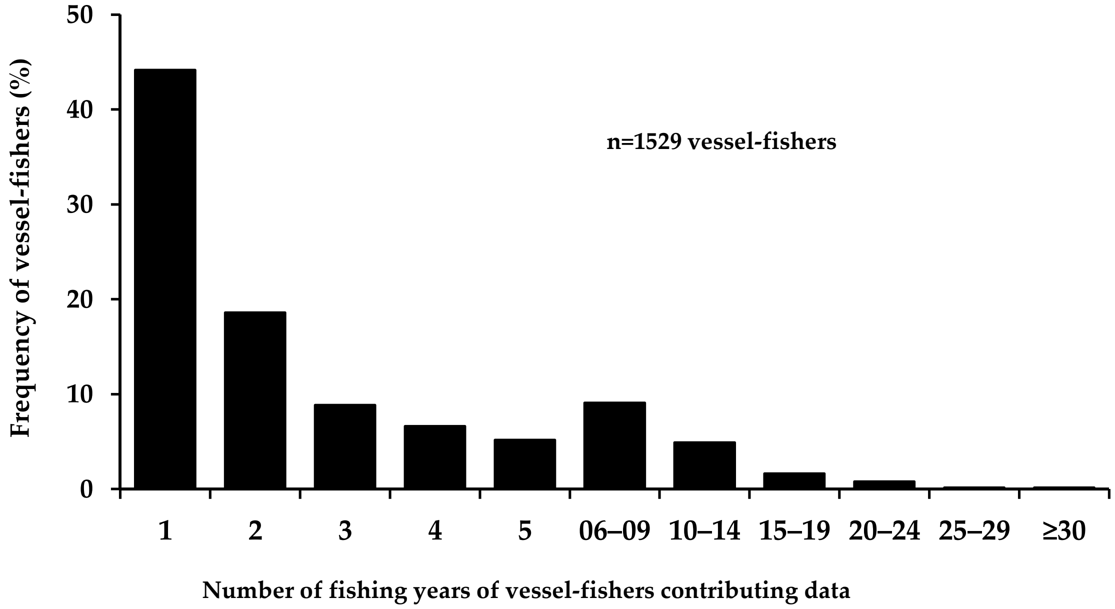
(b) Vessel-fisher performance as mean annual SRL targeted catch mass

Figure 3. Vessel-fisher mean annual CPUE (a) and mean annual catch (b) across WZ and EZ

Data: screened and non-selected; 1529 vessel-fishers contributing data for ≥1 fishing years during the period from 1978–79 to 2011–12; CPUE, catch mass per unit effort; SRL, southern rock lobster; WZ, Western Zone; EZ, Eastern Zone.

Data source: Fisheries Victoria CandE Database (11 January 2013)

(a) Per cent frequency of no. vessel-fishers contributing records for various fishing years



(b) Per cent of catch mass & records no. against cummulative number of vessel-fishers

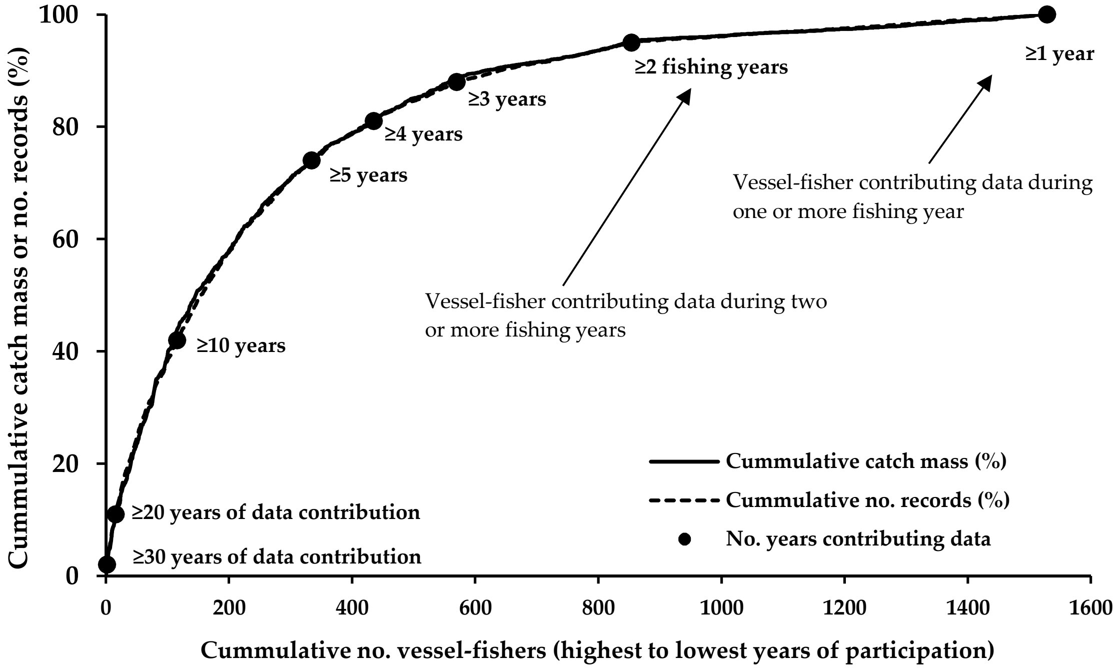
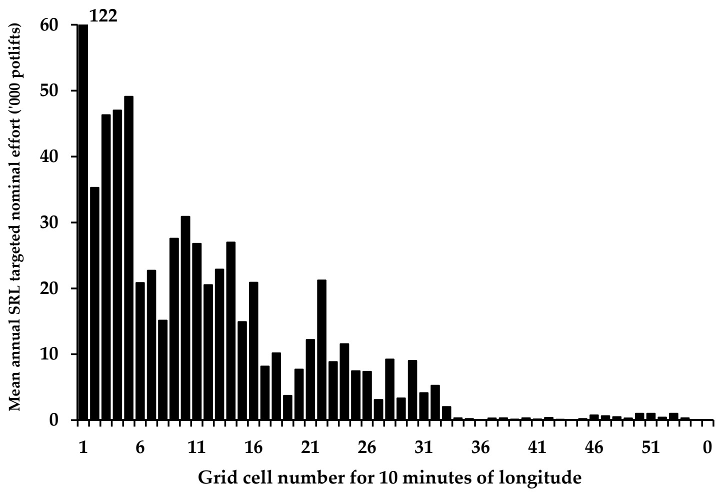


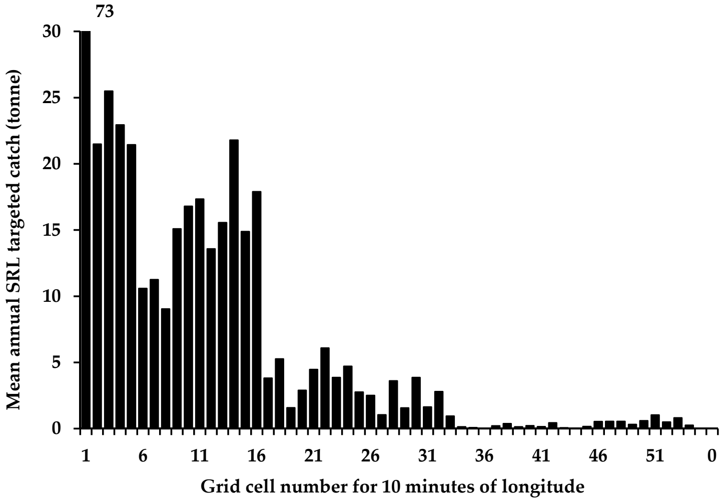
Figure 4. Catch mass, no. records and vessel-fisher participation across WZ and EZ

Data: screened and non-selected; 1529 vessel-fishers contributing data on SRL catch targeted at SRL or at SRL and GC during the period from 1978–79 to 2011–12; SRL, southern rock lobster; WZ, Western Zone; EZ,

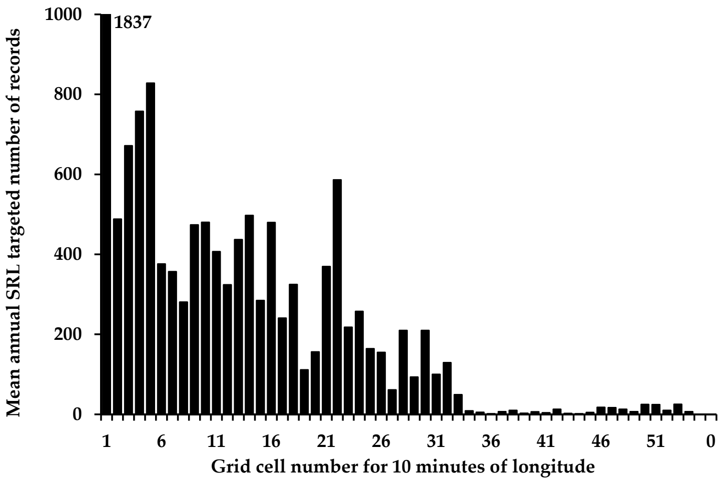
Data source: Fisheries Victoria CandE Database (11 January 2013)



(a) Distribution of mean annual nominal fishing effort



(b) Distribution of mean annual catch



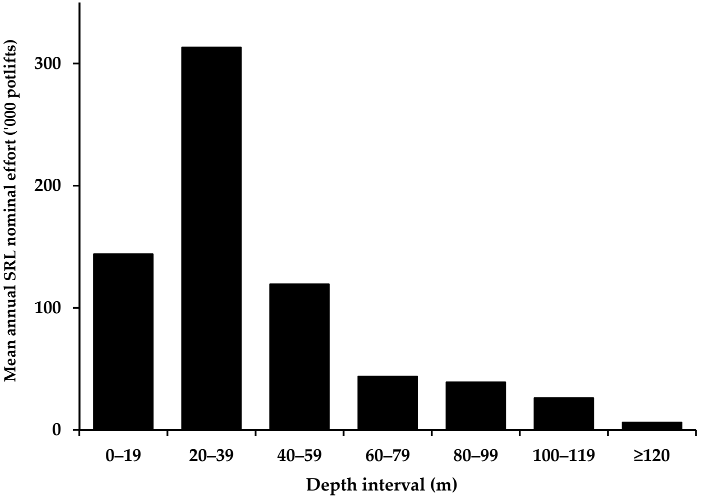
(c) Distribution of mean annual number of records

Figure 5. SRL targeted mean annual nominal fishing effort (a), mean annual catch mass (b), and mean annual number of records (c) for each grid cell for 10-minutes of longitude across WZ and EZ combined

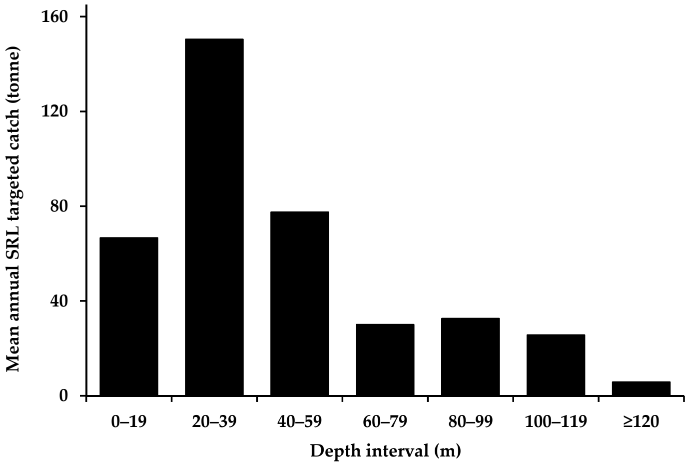
Data: screened and selected data; 570 vessel-fishers contributing data for ≥2 fishing years during the period from 1978–79 to 2011–12; SRL, southern rock lobster; WZ, Western Zone; EZ, Eastern Zone; grid cells for 10 minutes of longitude are shown in Fig. 1b.

Data source: Fisheries Victoria CandE Database (11 January 2013)

(a) Distribution of mean annual nominal fishing effort



(b) Distribution of mean annual catch



(c) Distribution of mean annual number of records

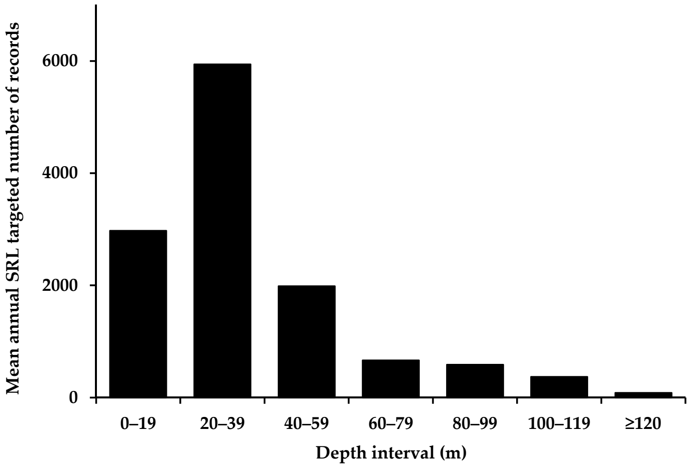
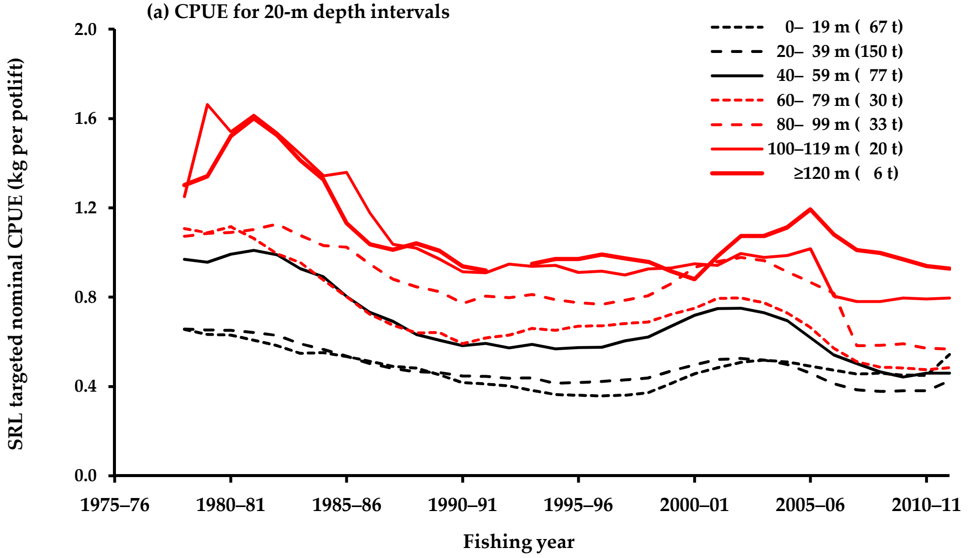


Figure 6. SRL targeted mean annual nominal fishing effort (a), mean annual catch mass (b), and mean annual number of records (c) by 20-m depth interval across WZ and EZ

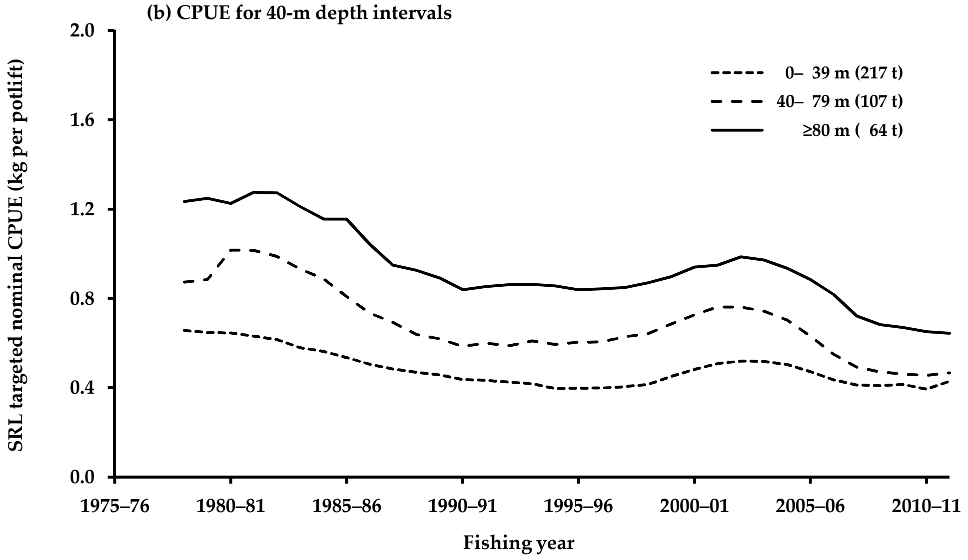
Data: screened and selected data; 570 vessel-fishers contributing data for ≥2 fishing years during the period from 1978–79 to 2011–12; SRL, southern rock lobster; WZ, Western Zone; EZ, Eastern Zone.

Data source: Fisheries Victoria CandE Database (11 January 2013)

(a) CPUE for 20-m depth intervals



(b) CPUE for 40-m depth intervals



(c) CPUE for 50-m depth intervals

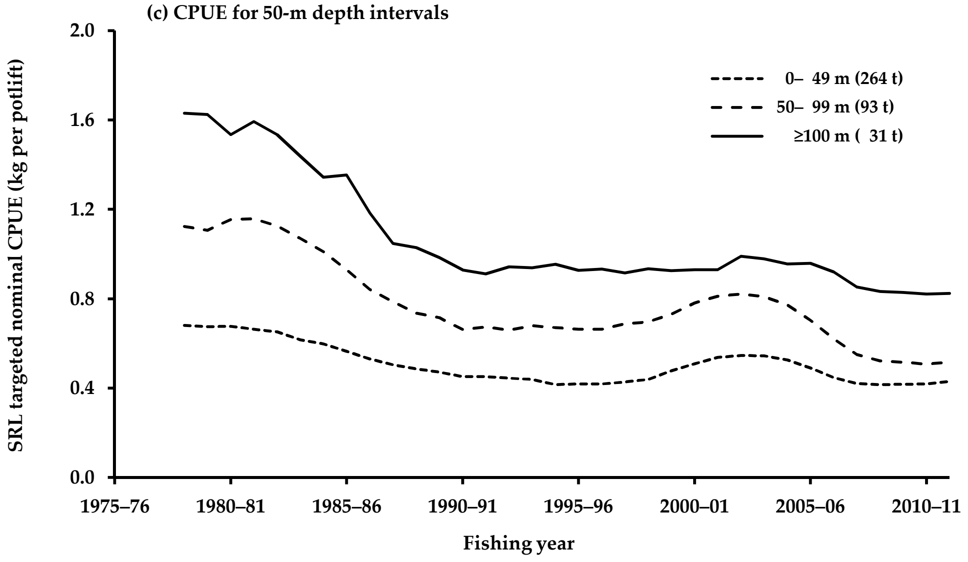
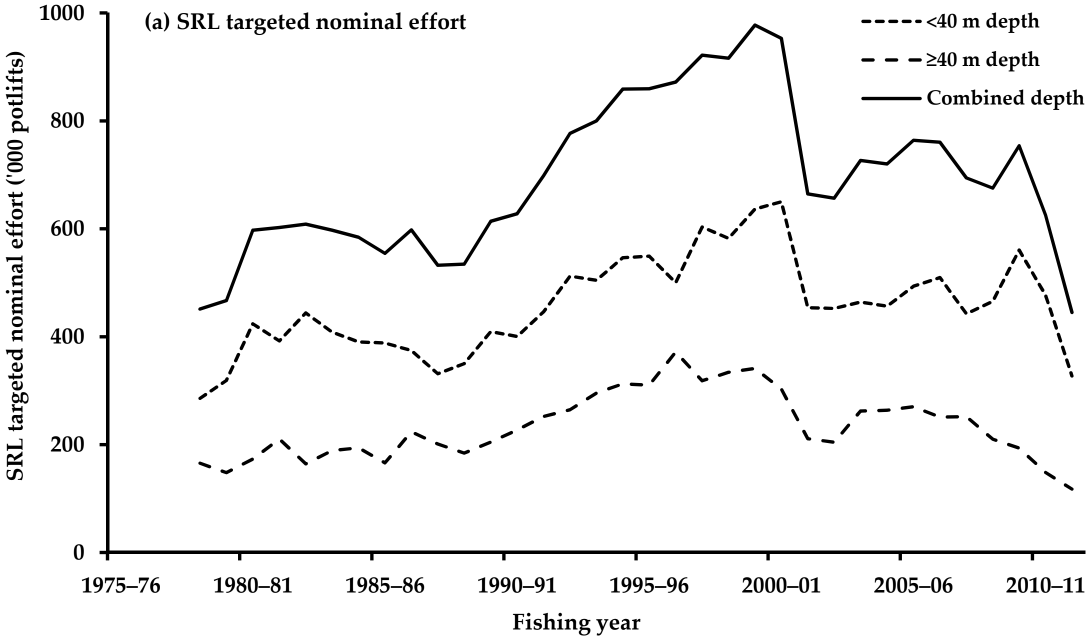


Figure 7. Trends in nominal CPUE (5-year running average) for selected depth-intervals across WZ & EZ

Data: screened and selected data; 570 vessel-fishers contributing data for ≥2 fishing years during the period from 1978–79 to 2011–12; mean annual catch mass in parentheses in legend; SRL, southern rock lobster; WZ, Western

Data source: Fisheries Victoria CandE Database (11 January 2013)



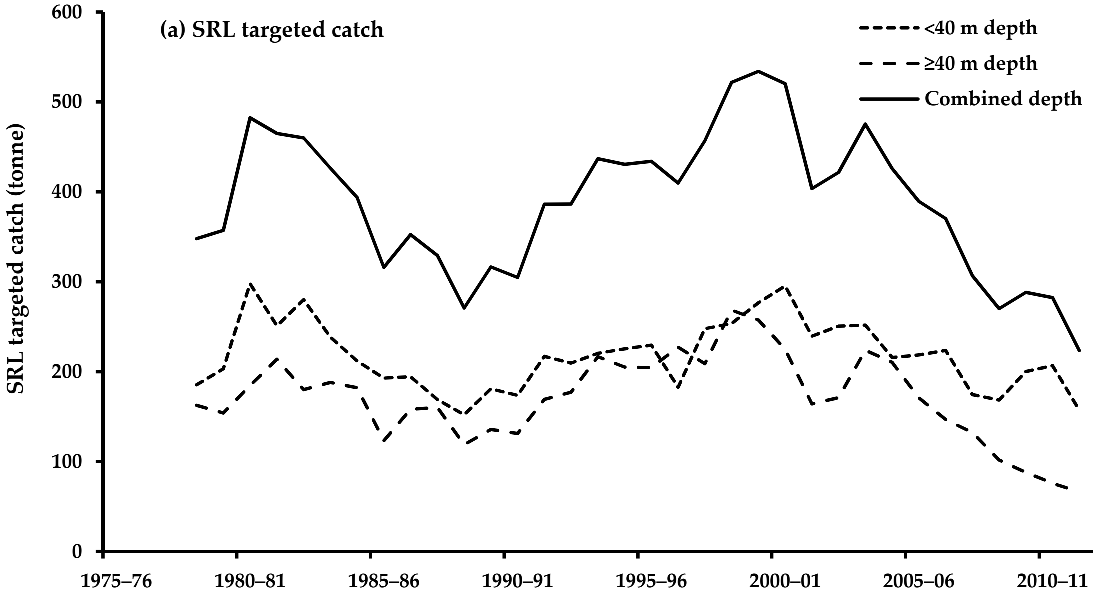
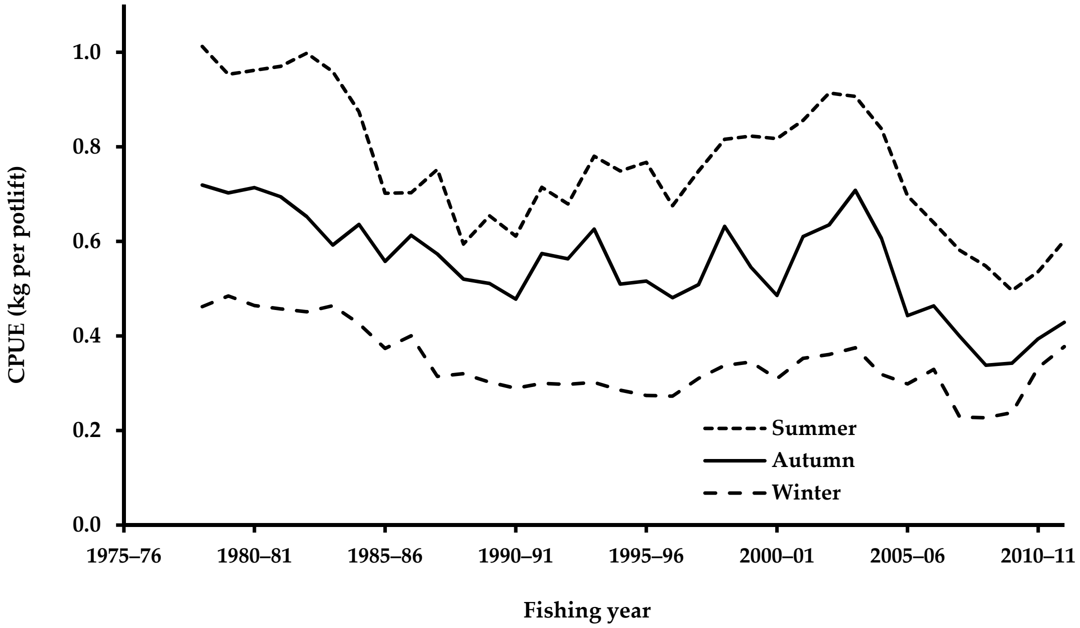


Figure 8. SRL targeteted nominal effort and catch mass trends in <40 m and ≥40 m depth ranges across WZ & EZ

Data: screened and selected data; 570 vessel-fishers contributing data for ≥2 fishing years during the period from 1978–79 to 2011–12; SRL, southern rock lobster; WZ, Western Zone; EZ, Eastern Zone.

Data source: Fisheries Victoria CandE Database (11 January 2013)

(a) Seasonal CPUE in Western Zone



(b) Seasonal CPUE in Eastern Zone

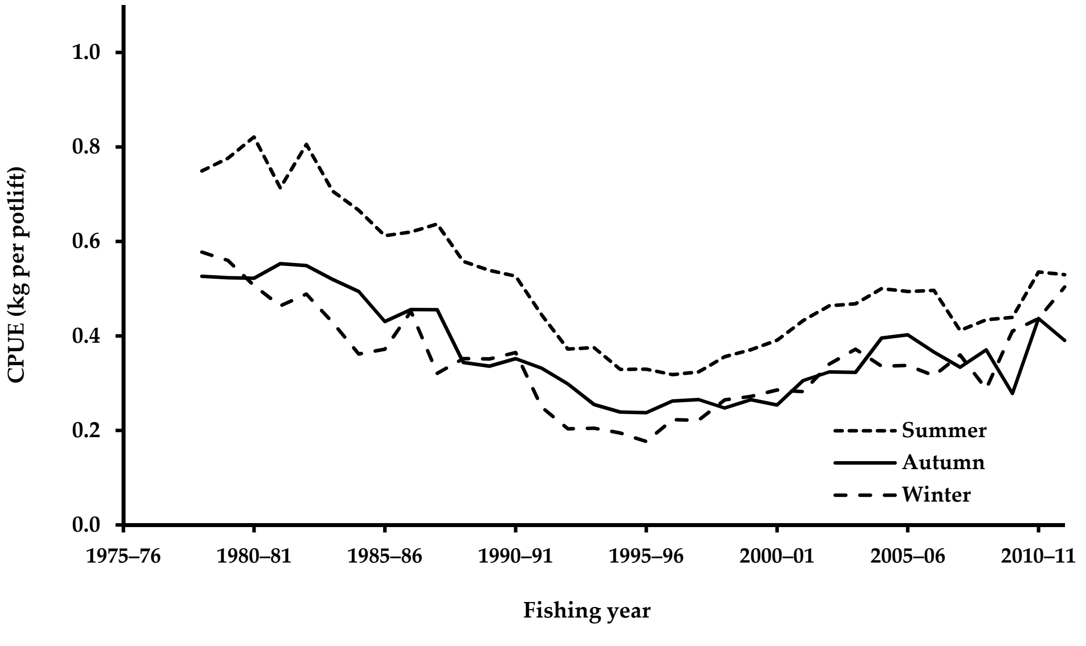


Figure 9. SRL targeted nominal CPUE trends by season in WZ (a) and EZ (b)

Data: screened and selected data; 391 vessel-fishers 391 in WZ and 196 in EZ contributing data for ≥2 fishing years during the period from 1978–79 to 2011–12; SRL, southern rock lobster; WZ, Western Zone; EZ, Eastern Zone; the seasons are defined as Summer (Nov–Feb), Autumn (Mar–May), and Winter (Jun–Sep).

Data source: Fisheries Victoria CandE Database (11 January 2013)

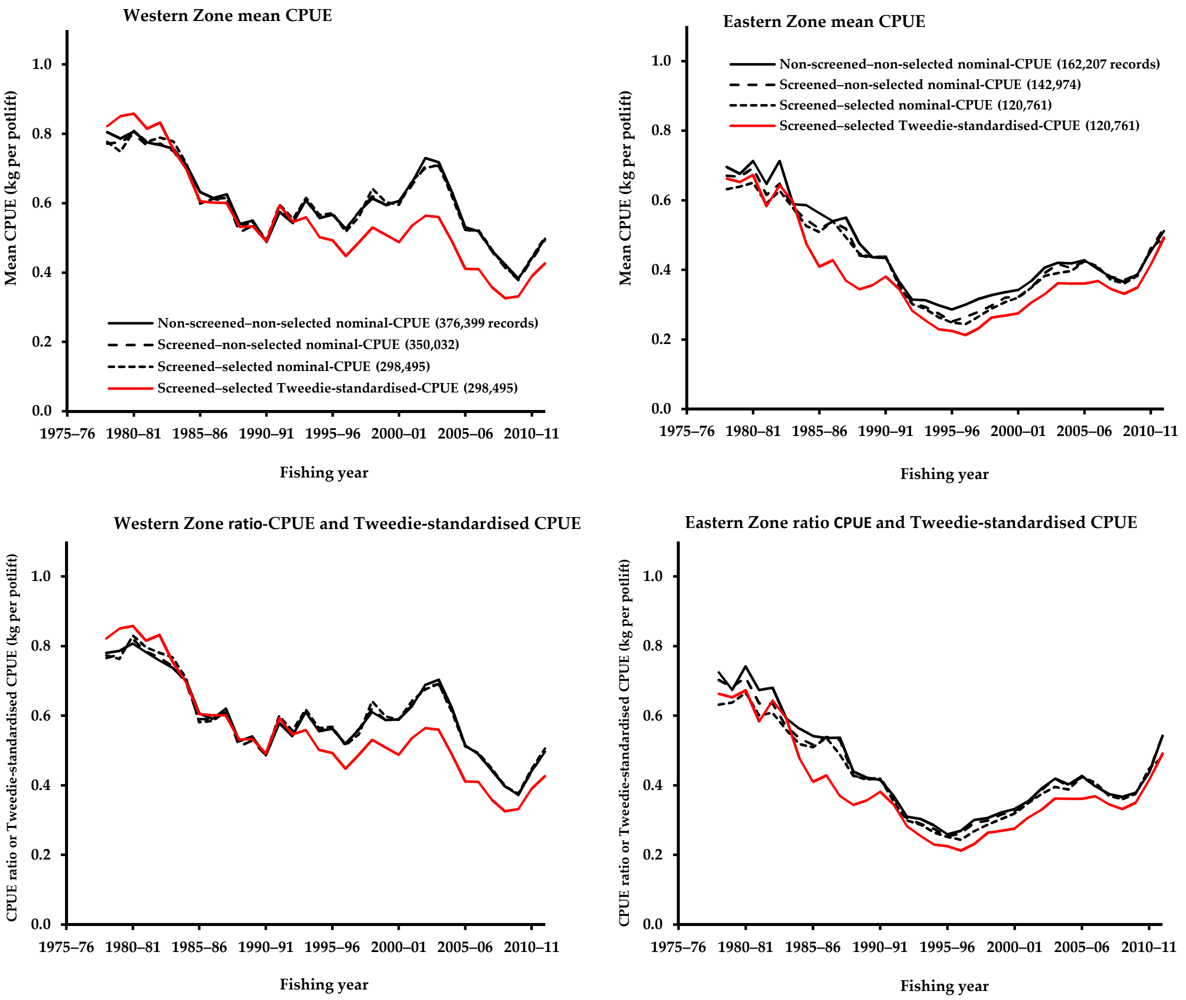


Figure 10. Comparison of trends in mean CPUE, ratio CPUE and Tweedie-standardised-CPUE for various levels of data processing

CPUE, catch mass per unit effort expressed as mean-CPUE or ratio-CPUE (total catch/total effort) for non-screened–non-selected data, screened–non-selected data (after 10 screening steps), and screened–selected data (selected vessel-fishers contributing data in >2 fishing years and ≥200 records), and Tweedie-standardised-CPUE for screened–selected data ; CPUE was mostly targeted at SRL or both SRL and GC (GC targeted records rejected except for non-screened–non-selected data); SRL, southern rock lobster; GC, giant crab.

Data source: Fisheries Victoria CandE Database (11 January 2013)

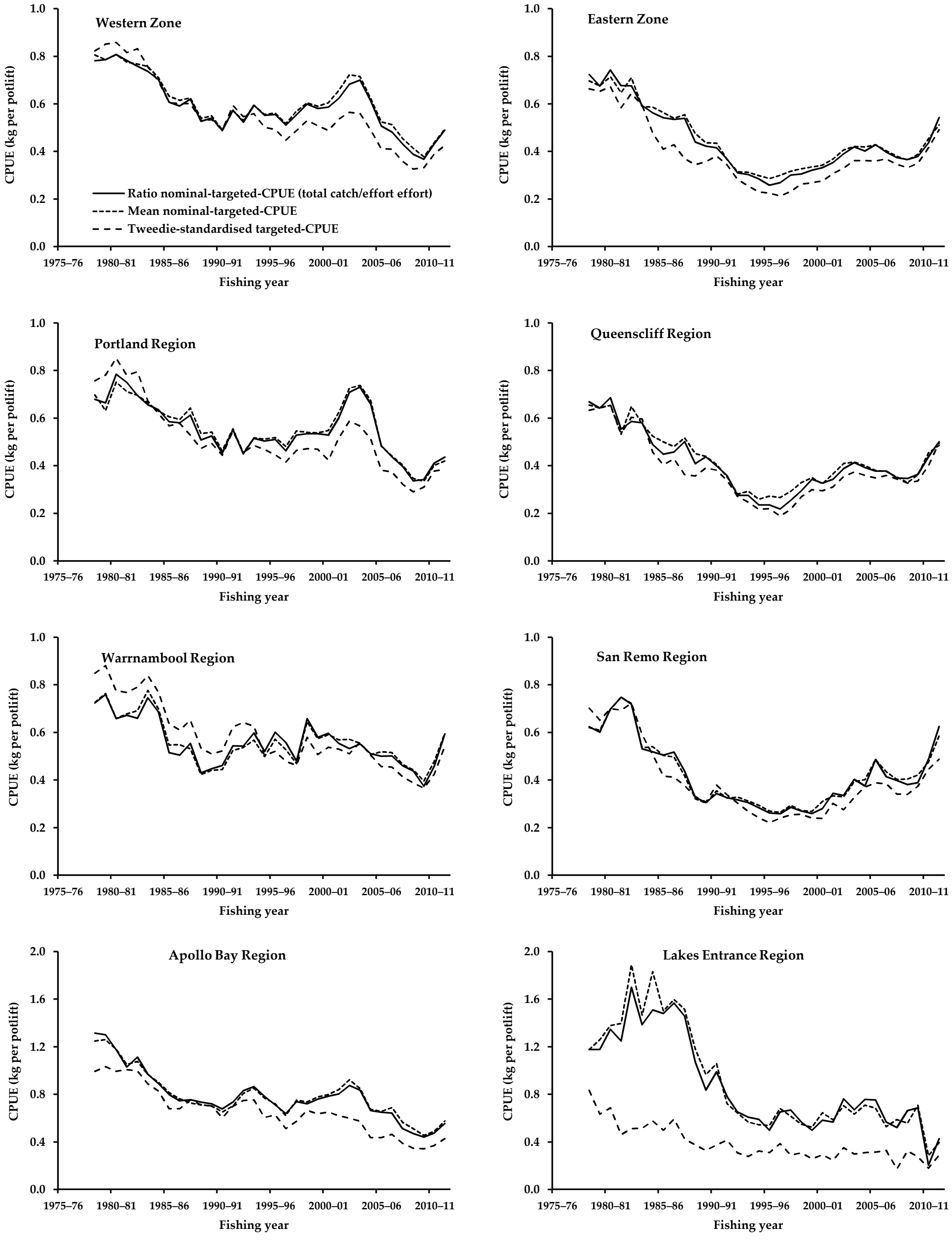
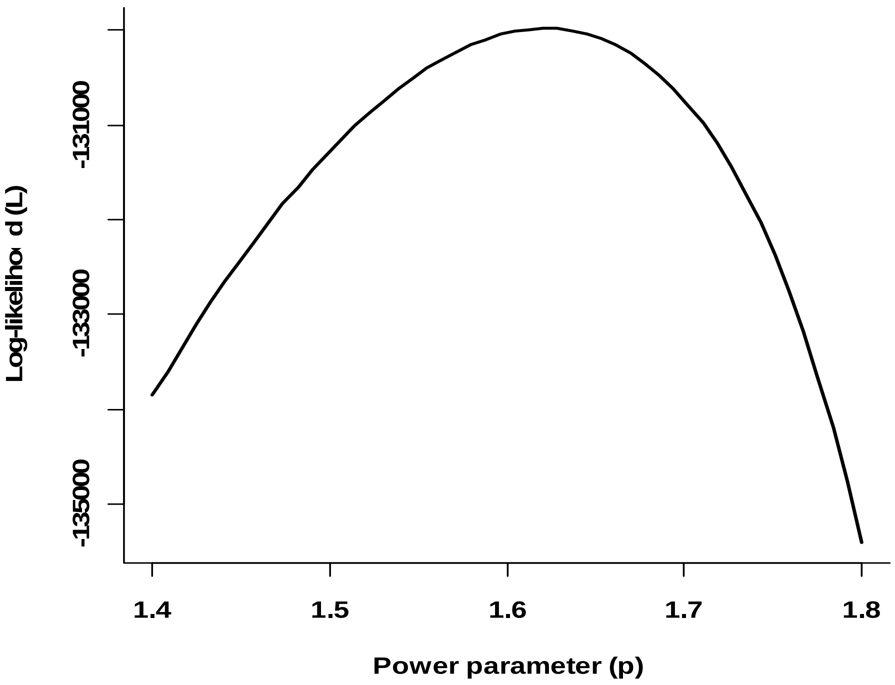


Figure 11. Comparison of trends in targeted ratio-CPUE, mean unstandardised CPUE with Tweedie-standardised CPUE for each zone and region

Data: screened and selected; CPUE, catch mass per unit effort targeted at SRL or both SRL and GC; ratio CPUE is total catch/total nominal fishing effort; SRL,

Data source: Fisheries Victoria CandE Database (11 January 2013)

(a) Log-likelihood function L against power parameter p in Western Zone



(b) Log-likelihood function L against power parameter p in Eastern Zone

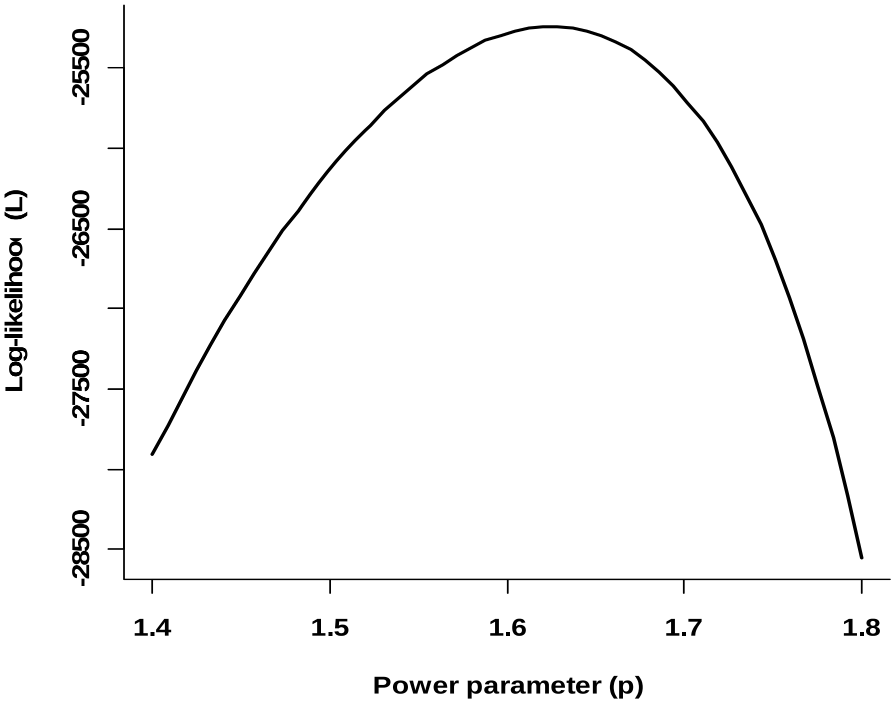


Figure 12. Log-likelihood function L against Tweedie power parameter p in the WZ and EZ

p= 1.620408 in the WZ and p= 1.628571 in the EZ for maximum log-likelihood values.

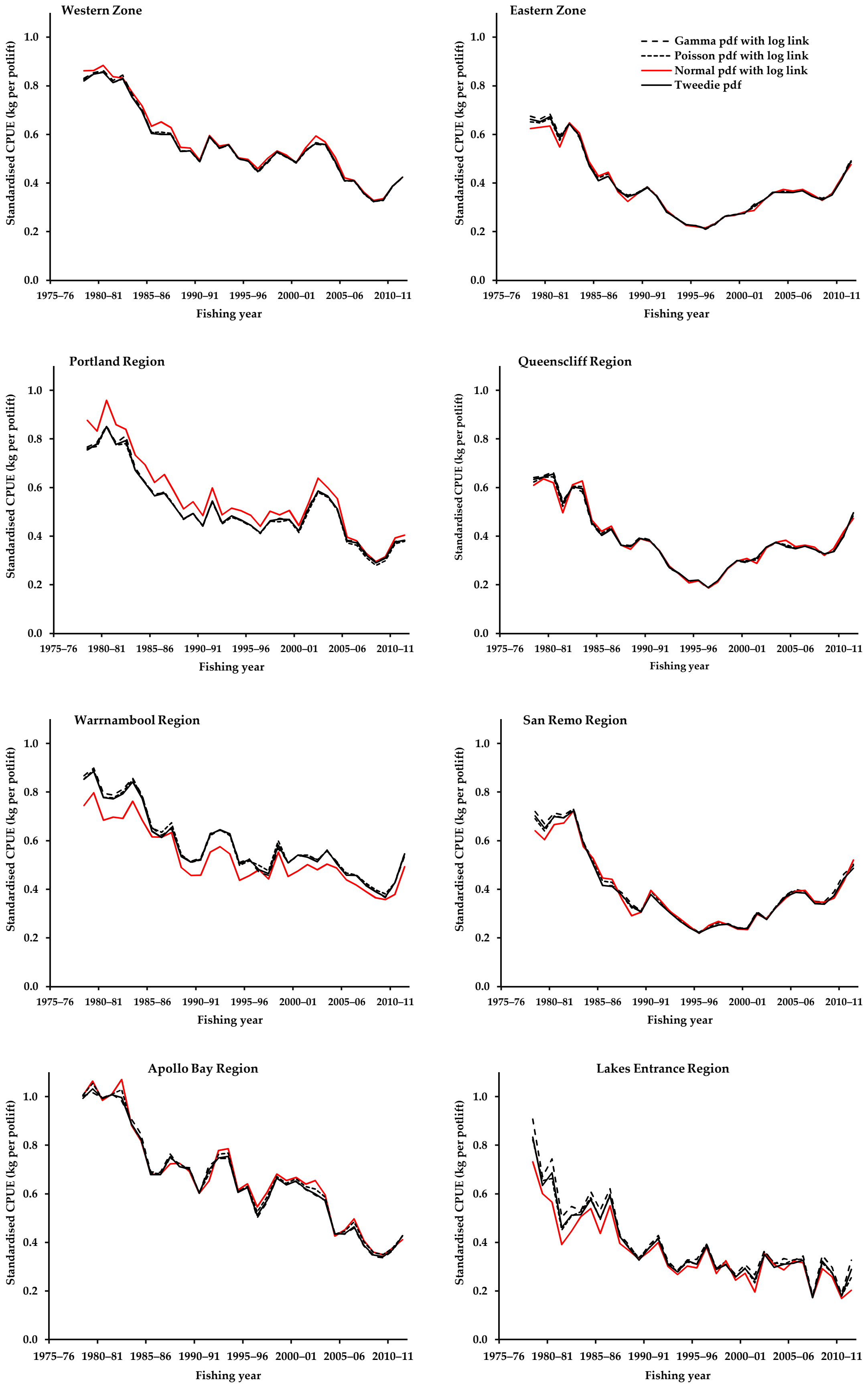
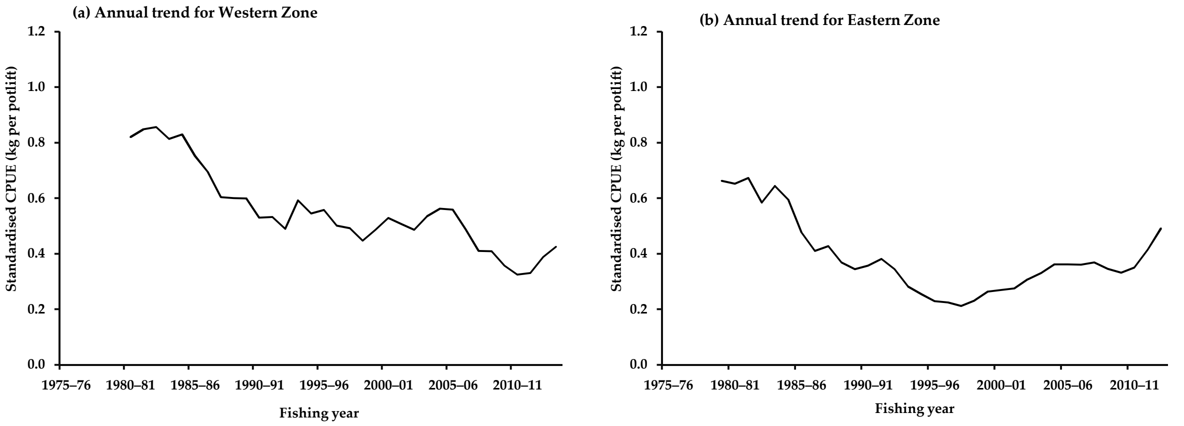
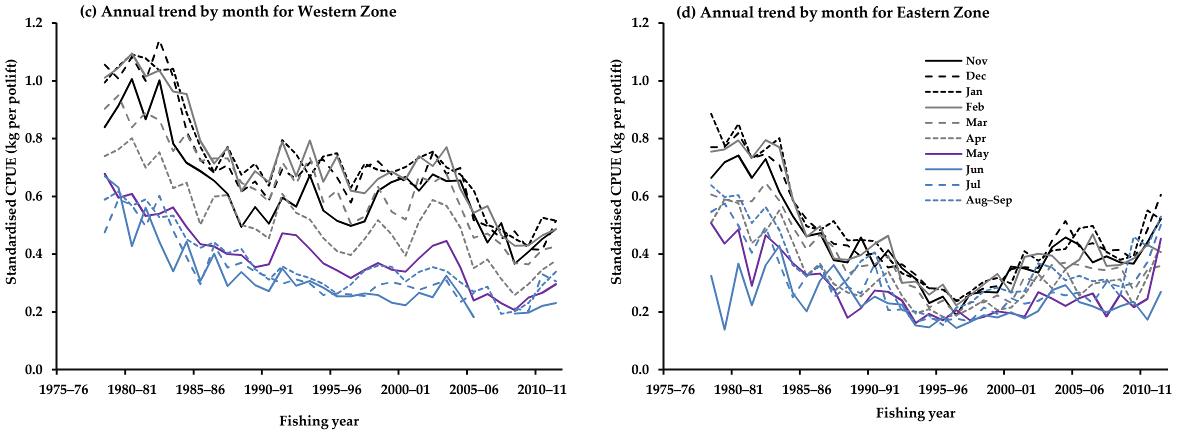
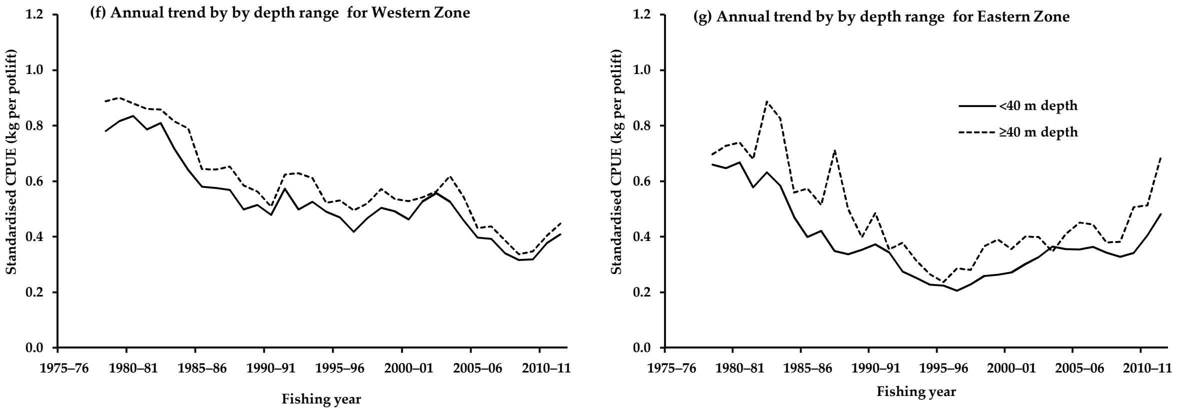


Figure 13. Comparison of SRL standardised-CPUE trends for several pdfs for each Victorian zone and region

Data: screened, selected and standardised; SRL, southern rock lobster; GC, giant crab; CPUE, catch mass per unit effort targeting SRL or







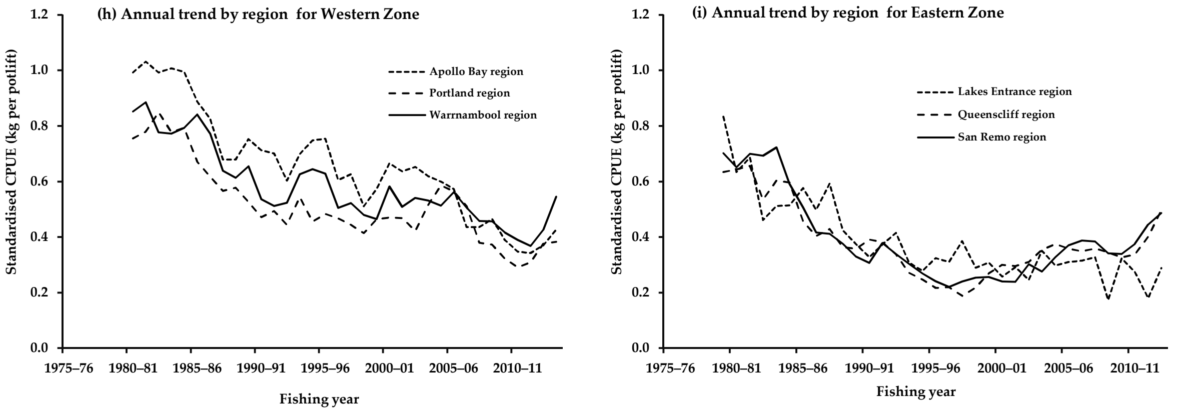


Figure 14. SRL standardised CPUE trends by month, depth-range and region applying the Tweedie pdf for each of the Western Zone and Eastern Zone

The trends are derived from the model interaction terms for fishing year x month, fishing year x depth-range, and fishing year x region.

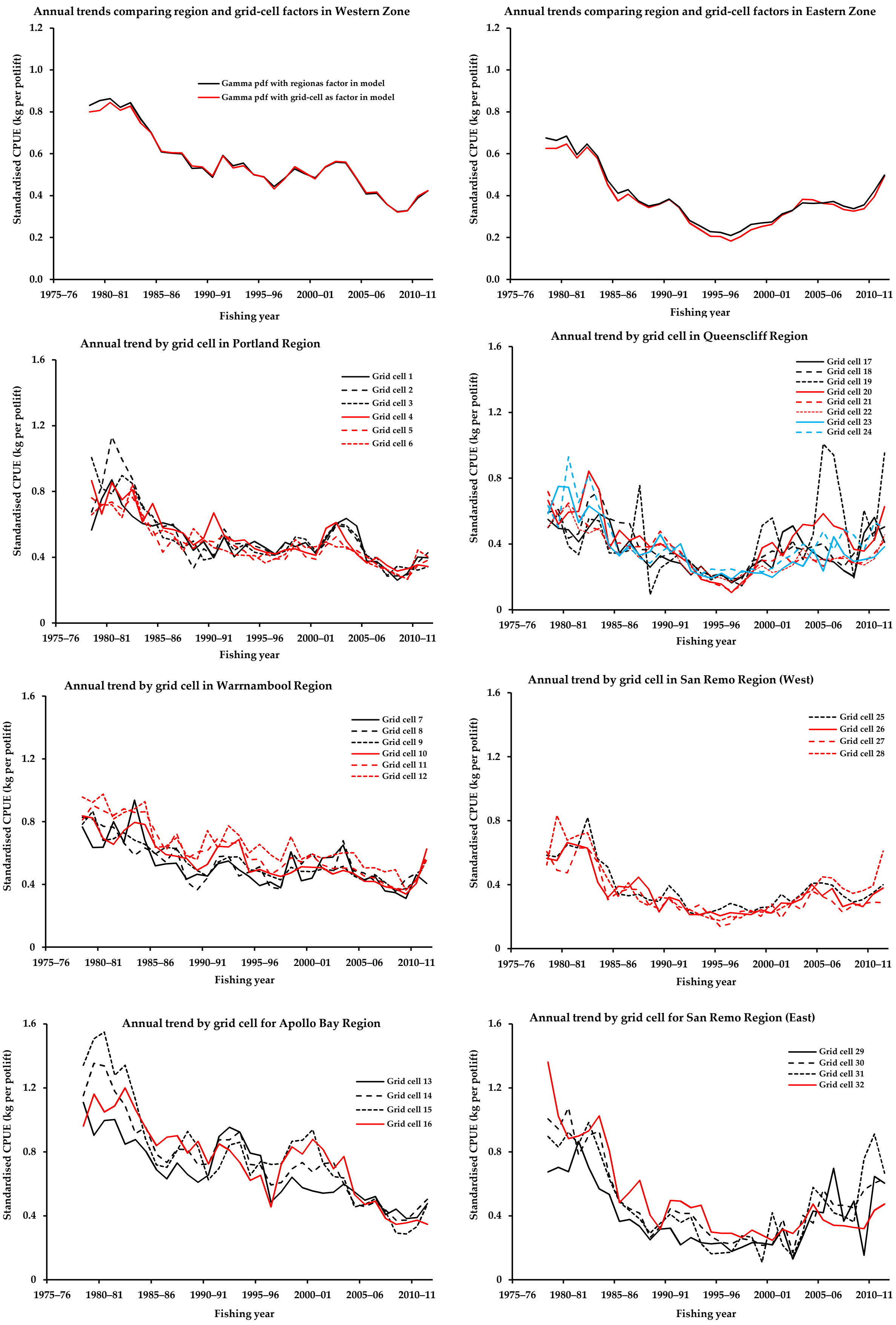
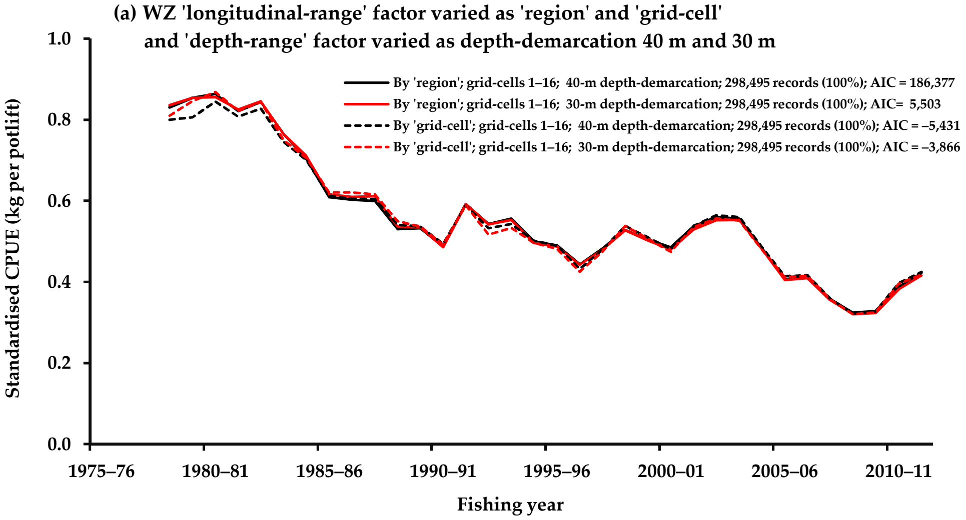
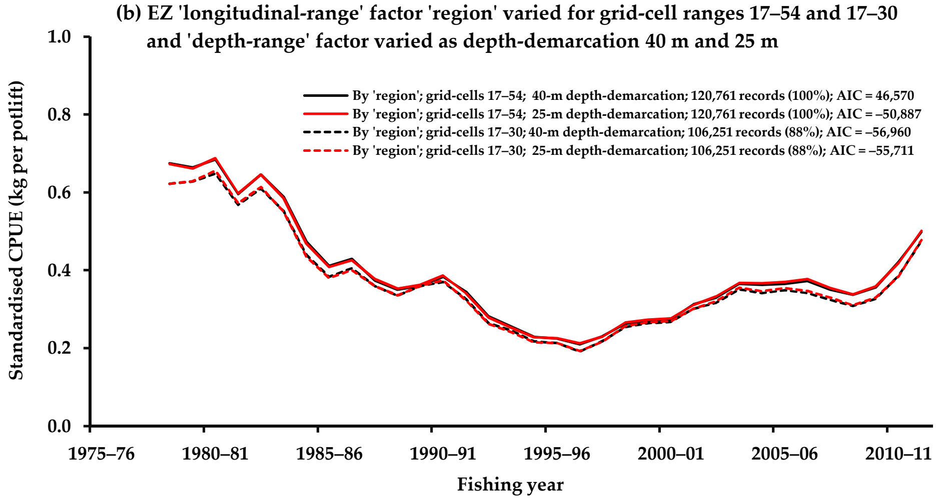


Figure 15. Comparing SRL standardised CPUE trends between region and grid-cell factors for model using gamma pdf with log link for each zone

The trends are derived from the model interaction terms for fishing year x region and fishing year x grid-cell.


(a) WZ 'longitudinal-range' factor varied as 'region' and 'grid-cell' and 'depth-range' factor varied as depth-demarcation 40 m and 30 m


(b) EZ 'longitudinal-range' factor 'region' varied for grid-cell ranges 17–54 and 17–30 and 'depth-range' factor varied as depth-demarcation 40 m and 25 m

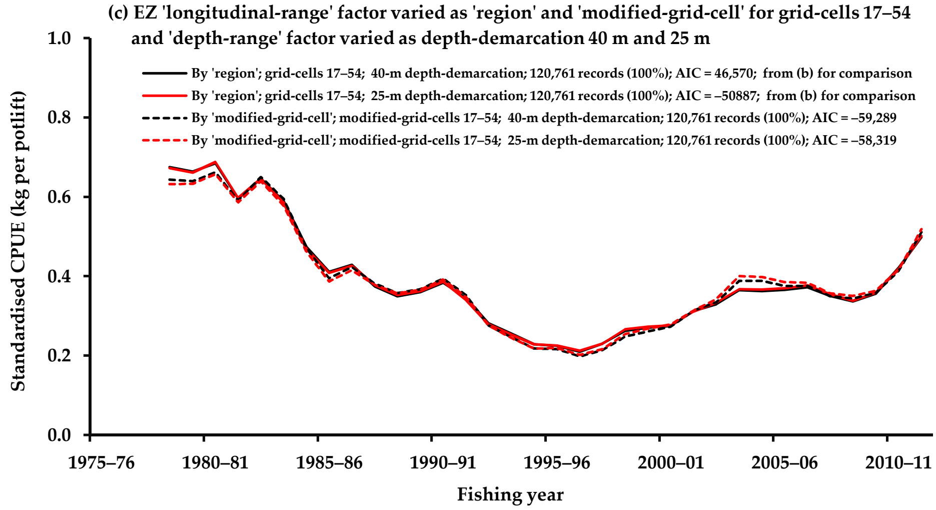

(c) EZ 'longitudinal-range' factor varied as 'region' and 'modified-grid-cell' for grid-cells 17–54 and 'depth-range' factor varied as depth-demarcation 40 m and 25 m

Figure 16. Standardised CPUE trends using alternative spatial factors in the model

'Longitudinal-range' factor was varied as 'region' and 'grid-cell' (or 'modified-grid-cell' in the EZ) and 'depth-range' was varied as 40-m and 30-m depth-demarcation in the WZ (a) and as 40-m and 25-m depth-demarcation in the EZ (b), but in the EZ, the 'longitudinal-range' factor was varied to include only the range of grid-cells 17–30 (truncated EZ) and the full range of grid-cells 17–54 (whole EZ) (see Fig. 1b). Because grid-cells 31–54 variously had strata with nil or a low number of observations, they were grouped to provide 4 'amalgamated grid-cells' (31–32, 33–36, 37–49, and 50–54), which together with the 20 grid-cells 11–30 (trucated EZ) (where none of the spatial strata had nil or a low number of observations) were designated as 'modified-grid-cell' and applied in the model as factor 'modified-grid-cell' (c). EZ, Eastern Zone; WZ, Western Zone; AIC, Akaike Information Criterion.

Environmental influences on daily commercial catch rates of South Australia's southern rock lobster (*Jasus edwardsii*)

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Abstract

Stock assessments for southern rock lobster (*Jasus edwardsii*), as for most fisheries, rely on catch rate as an index of relative abundance. The extent to which environmental catchability factors, instead of abundance, may be affecting catch rates was examined. A weighted linear regression was carried out of daily-aggregated commercial catch rates for South Australia's Southern Zone on several environmental variables in addition to year and month. Log-transforming of catch rates was needed to homogenise the variance and a power function of daily potlifts was needed for the regression weights to remove strong non-normality in residuals and reduce large overdispersion for days with few potlifts. Model pruning via backward selection resulted in the following variables remaining in the model: wave height and period, lagged wave height, bottom temperature, moon phase, and a spatial index. These variables, in the weighted regression, explained 7% of total variance in transformed daily catch rates while another 84% was explained by month and year factors. Wind stress (including alongshore) and sea surface height did not explain much of the variance in the presence of the other named variables. A negative relationship was found between catch rate and each of bottom temperature and same day wave height. For days just prior to full moon, and wave height over past recent days, a positive relationship was found.

Introduction

The southern rock lobster (*Jasus edwardsii*) fishery is the highest valued wild commercial fishery in South Australia being worth $81.3 million for the 2010/11 financial year (Knight and Tsolos, 2012). Since 1968, the fishery has been divided into two management regions (Figure 1), namely the Northern Zone and the Southern Zone (Lewis, 1981a), the latter being the focus of this study. The zones are further sub-divided into Marine Fishing Areas (MFAs) for statistical purposes. In recent years, the Southern Zone has comprised around 80% of the total state rock lobster catch (1,810 tonnes) with the majority caught in MFAs 55, 56, and 58 (Figure 1) (Linnane et al., 2011a).

A range of both input and output controls are used to manage the Southern Zone fishery (Sloan and Crosthwaite, 2007). Fishing seasons extend from October to May of the following year (seasons are referred to by start-of-season year) and a minimum legal size of 98.5 mm carapace length exists. Each fisher may own no more than 100 pots and the total number of licences in the fishery is limited to 181. Since 1993 a total allowable commercial catch (TACC) system has been in place with the TACC for the 2011 season being set at 1250 tonnes (Linnane et al., 2011b). Current harvest strategy decision rules utilise catch per unit effort (CPUE) to determine annual TACCs as part of the stock assessment process. These rules are designed to maintain exploitation rates at desired levels (Punt et al., 2012). One of the basic assumptions in this management strategy is that change in catch rate reflects change in relative lobster abundance. However, factors other than abundance may affect catch rates and these are often assumed to act as a time-varying multiplicative factor on abundance known as catchability (Arreguin-Sanchez, 1996).

Temperature is known to impact catch rates for many species of lobster. The most common result found in the literature is that of a positive association between catch rates (or catchability) and temperature for species such as *Homarus americanus* (McCleese and Wilder, 1958; Drinkwater et al., 2006), *Homarus gammarus* (Smith et al., 1999; Schmalenbach, 2009), *Panulirus cygnus* (Morgan, 1974), and *J. edwardsii* (Ziegler et al., 2004). However, Courchene and Stokesbury (2011), who compared lobster trap catches with scuba dive surveys, reported a negative association between *H. americanus* catch rates and bottom temperature.

Ocean swell off the South Australian coast is associated with rapidly changing sea-states including storm fronts passing closely along the coastline (Middleton and Bye, 2007). Significant sediment re-suspension may occur along the continental shelf from sufficiently high swells and bottom currents (Middleton and Bye, 2007). Fishers in Western Australia have reported that daily catch rates were influenced by sea swell, wind strength, tidal movement and water turbidity (Morgan, 1974). In addition, sea swell on the days prior to fishing had a significant positive impact on catch rates of *P. cygnus* (Srisurichan et al., 2005). A study of *Panulirus japonicus* catch rates also found a positive association with large swells (Yamakawa et al., 1994). For *J. edwardsii* literature on the relationship between ocean swell and catch rates is limited. However, South Australian rock lobster fishers anecdotally report improved catches on the days after a big swell.

The lunar cycle is known to affect catch rates of several species of rock lobster around the world, including spiny lobsters *P. cygnus* (Morgan, 1974; Srisurichan et al., 2005) and *P. japonicus* (Yamakawa et al., 1994) with higher catch rates generally linked to periods around the new moon. For *J. edwardsii* a Tasmanian research study found no difference in spring catch-rates between the new moon and full moon (Ihde et al., 2006). However, as with sea conditions, South Australian rock lobster fishers anecdotally report observations of improved catch rates in the days just prior to the full moon.

Wind-induced cold water upwelling is a regular seasonal feature of the South Australian Southern Zone fishery (Schahinger, 1987). Known locally as the "Bonney upwelling" this generally impacts the relatively narrow continental shelf between Cape Jaffa and Portland (Figure 1). For regions experiencing strong upwelling, wind, sea surface height (SSH), and water temperature are closely related via Ekman dynamics, with summer alongshore winds driving a decrease in SSH and colder bottom temperatures (Middleton et al., 2007). This is evidenced by correlations found among SSH, alongshore current, local alongshore winds, and bottom temperatures for the Bonney Coast region, with lags ranging from 0 to 3 days (Schahinger, 1987).

The primary aim of this study was to examine the daily effect on catch rates of environmental variables including bottom temperature, waves, moon phase, wind, and SSH within the Southern Zone rock lobster fishery.

Methods

Data

Commercial fishing data were recorded as daily totals by commercial fishers and entered into a daily logbook submitted monthly. Mandatory reporting fields exist for fishing effort (daily potlifts) and landed catch (numbers and weight (kg) of live non-spawning legal-sized lobsters (Linnane et al., 2011a). Daily catch rates (kg/potlift) for the Southern Zone fishery were calculated for each day of fishing from October 1998 to May 2009, by first aggregating catch and effort over fishers for each day, and then dividing the total daily catch weight by the total daily potlifts. There were no days that had fishing effort but for which the value for total daily catch weight was 0.

Fishers also record average daily depth fished as well as the principal MFA where fishing takes place. A single spatial index was computed to reflect average MFA fished by all fishers fishing on a given day. Index values were assigned to each of the four main MFAs following sequentially north-west to south-east along the coast namely, 1 = 51, 2 = 55, 3 = 56, 4 = 58 (which comprise >99% of the daily logbook data), with averages of these indices then calculated per day.

Covariate data available included bottom temperature, wind, SSH, moon phase, and ocean wave (swell) information. Most of the environmental covariate data existed at the sub-daily level of resolution. The period from midday to midday (midnight centred), rather than the more conventional midnight to midnight period, was used in the aggregation to the daily level in order to more fully capture the typical period over which pots are set and subsequently hauled by fishers. This period for calculation is based on the fact that pots are dropped overnight and lifted up again at first light (Linnane et al., 2011a).

SSH (m) was sourced from the Australian Bureau of Meteorology (National Tidal Centre) from a sea level gauge located on the coast near Portland (point "c" in Figure 1). These data, originally obtained from the Bureau of Meteorology (BoM), were filtered to remove incoherent low energy fluctuations that have little energy or tidal effects. Larger oceanic water movements such as coastally trapped waves and upwellings remained in the filtered SSH series. The data extended from February 1993 to March 2010, with most of January 1999 missing.

Wind data, originally obtained from BoM, were sourced from the Australian Bureau of Meteorology at a location on land near Portland (point "c" in Figure 1) at the local Cashmore airport. The data extended from January 1990 to October 2008, with most of January 2000 missing. Components of the data included wind speed (m/s), wind direction (degrees True), and wind stress (all in Pascals) for north-south, east-west, alongshore, and cross-shore directions, with shore stress direction = −45 degrees True.

Daily average bottom temperatures (degrees Celsius) were compiled from hourly recordings of a bottom temperature logger, maintained by SARDI Aquatic Sciences, located at ~60 m depth off Southend (point "b" in Figure 1).

The wave data set was output from a wind-wave oceanic model named WAVEWATCH III which is run by the US government NOAA National Weather Service NCEP (waves page at polar.ncep.noaa.gov). Statistical outputs from the model include wave height (m) and wave period (seconds). Five point locations were obtained but only one site (80 m deep, point “a” in Figure 1) was chosen to use in the catch rate model as the other 4 were at unrepresentative depths or located well outside the fishery region. This wave data set extract is continuous from February 1997 to March 2010.

Moon phases were obtained by first accessing data on moon fraction illuminated at midnight from 1994 to 2009 from the U. S. Naval Observatory website (MoonFraction page at aa.usno.navy.mil/data/docs) for the Chamorro time zone. Eight discrete ordered moon phases were then computed from the moon fraction illuminated data by creating eight periods per lunar cycle each spanning 0.25 of moon fraction illumination, with the first phase variable centred on 0 illumination fraction describing the new moon period.

The number of days that could be used in the analysis was substantially reduced by the inclusion of some of the environmental covariates. Bottom temperature was the least available of all covariates which resulted in approximately a 50% reduction of sample days between 1998 and 2008. Days with data were also deleted if these would otherwise form very sparse represented months or seasons. The total number of days in the model is 1258 (Table 1) with an overall geometric mean catch rate of 1.2 kg per potlift. Month values 1 to 8 are in order from start to end of the fishing season (October to May) with month 9 being the off-season (June to September inclusive; May to September prior to 2003).

Error model

The lobster catch rate, U_t, is calculated as the ratio of total catch weight C_t in weight (kg) divided by effort E_t in total potlifts (aggregated over all fishers fishing) on day t in the fishery,

$$U_t = C_t / E_t. \tag{1}$$

The model assumes that U_t is a multiplicative function of K_t, which is catchability that varies daily with the marine environment, and lobster abundance B_t, as in Equation 2

$$U_t = K_t B_t \varepsilon_t, \tag{2}$$

where $\varepsilon_t \sim LN(\lambda,\sigma^2)$ is independently log-normally distributed observation error with distribution parameters $\lambda = 0$ and σ^2.

When the catch rates are log-transformed (Venables and Dichmont, 2004) the model becomes that of an ordinary Gaussian linear model,

$$y_t = \log(U_t) = \mu_t + e_t, \tag{3}$$

where y_t is a normally distributed response variable, with parameters $\mu_t = E(y_t) = \log(K_t B_t)$ and $\sigma_t^2 = Var(y_t)$, with $e_t \sim N(0,\sigma_t^2)$ being independently normally distributed errors. In addition to the mean, μ_t, of the log-transformed catch rates, the variance, σ_t^2, of the log-transformed catch rates is also time-dependent on account of sample size variability in daily fishing effort, and so $\sigma_t^2 = \sigma^2/\omega_t$ where ω_t is a variance weighting equal to a function of potlifts (see regression weight subsection and supplementary data).

Estimation involves $\mu_t = q_t + f_t$, where $q_t = \log(K_t)$ and $f_t = \log(B_t)$ are terms for log-transformed catchability and abundance respectively. Relative variation in lobster abundance B_t is assumed to be quantified by a linear combination of terms involving season and month. Log-transformed daily catchability is considered as a linear combination of *k* covariate terms, $q_t = \beta_0 + \sum_{i=1}^{k} \beta_i X_{t,i}$, where $X_{t,i}$ is a datum of covariate *i* for day *t* that may be continuous (such as bottom temperature) or categorical (moon phase) with β_i defining the corresponding estimated coefficient parameter. The β_i may vary by fishing season or month and this would model interaction between time and environmental covariates. β_0 is the log-transformed constant of proportionality between the model components and U_t.

Regression weights

Estimation required regression weightings, ω_t (Equation S4), to account for large daily variation in fishing effort (potlifts), which are equal to the day’s pot count raised to a power less than 1. These provide a form of heterogeneous variance modelling involving $\omega_t = (\text{pots-lifted-on-day-t})^{1/m}$ ($m \geq 1$). For all days ω_t is larger for days with more effort (i.e. more potlifts) implying greater precision in catch rate data that involve more fishing events (i.e. sample size) via imposing correspondingly reduced variance. The larger the value of *m* the less variance is reduced for days of high effort relative to days of low effort (see supplementary data, Figure S1). Note that prior to application in the regression model the ω_t were divided by their mean in order to standardise residual diagnostic outputs (but this has no impact on reported results).

A funnel shape of the plot of residuals versus daily potlifts (results not shown) when $\omega_t = 1$ (i.e. no weighting) suggested a power function of potlifts. $m > 1$ was justified based on several considerations including the impact on catch rate variance in the presence of cluster sampling of pots by fishers and heterogeneity of this between days (see supplementary data). A value of $m = 3$ was determined to be optimal by considering residual diagnostic plots (e.g. dispersion versus potlifts, QQ) for the full-term starting model described in the model backward selection process (see below). In addition to reducing over-dispersion for days with low effort, this weighting also had the desirable effect of eliminating strong non-normality in residuals (results not shown) evident when m was lower or higher.

Model development and implementation

Model selection rules

The process of arriving at a final model involved backward selection of covariate terms. The entire data were restricted to days for which all the covariates as well as fishery data were available to keep the data set the same throughout the model selection process. The small sample corrected Akaike Information Criterion (AICc) (Burnham and Anderson, 2004) was used since the ratio of number of days with data to number of model parameters is small (<20). At each step, the term deleted was the one resulting in the reduced model with the lowest AICc, until deletion of no term decreased AICc by more than 2 units. After this a further step-wise selection process was performed by deleting, at each step, the term that decreased the weighted regression's adjusted proportion variance explained (adjR^2) the least, until deletion of no term decreased adjR^2 by less than 0.25%. The adjR^2 criterion was applied to avoid retention of parameters that accounted for very little variability in the data (Maunder and Punt, 2004).

Note that due to regression weighting, the adjR^2 statistic does not exactly represent the proportion of variation explained in the log-transformed catch rates by the covariates data, but rather it is a measure of proportion of variation in weighted log-transformed catch rates that can be accounted for by the weighted covariates. This potentially results in a positive bias in adjR^2 because the weighted data is likely to be less noisy than the unweighted data (Willett and Singer, 1988).

Model implementation

The statistical software used for the regressions was R (version 2.13.0 (2011-04-13) Copyright (C) 2011 The R Foundation for Statistical Computing ISBN 3-900051-07-0). The main R function used was glm(), which implements generalized linear models (GLMs) (Venables and Dichmont, 2004), with family option set to "gaussian" (with default identity link), option na.action set to "na.exclude" to account for missing values in the inputs. The weights option in glm() was set to the function of pots described above which implements the Gaussian weighted linear regression model.

Plots of standardised residuals versus predicted values for the log-transformed catch rate models were examined for trend, and the normality assumption in the errors of the regression were examined using quantile–quantile (QQ) plots of standardised residuals. Identification and impact of any outliers were examined using function outlierTest() (from R package *car*) on studentized residuals using Bonferonni corrected p-values (5% significance level), and influential data were examined using leverage plots which include Cook's distance statistics. The effect of collinearity between covariates was examined by means of sub-model comparison and by examining variance inflation factors (VIFs) using function vif() (from R package *car*).

Model specification

The starting glm model in the regression backward selection process included covariates plus their bivariate interactions with fishing season and month. Included also were moving average lag (over 1 to 5 days) versions of wave height, bottom temperature, and alongshore wind stress, thought on *a priori* physical grounds, to involve a potentially delayed catch rate response. The main effect terms entering into the initial model for the mean of log-transformed catch rates are shown in Equation 4 to which are also added the interactions and lags.

$$\mu_t = \mathrm{Sn} + \mathrm{Mn} + \mathrm{Sn} : \mathrm{Mn} + \mathrm{WaveH} + \mathrm{WaveP} + \mathrm{T} + \mathrm{Moon} + \mathrm{SSH} + \mathrm{Wtau} + \mathrm{WtauAS} + \mathrm{MFAi} + \mathrm{Depth} \quad , \qquad (4)$$

where Sn = fishing season and Mn = month, hence Sn+Mn+Sn:Mn is the monthly time trend component. WaveH = wave height, WaveP = wave period, T = bottom temperature, Moon = moon phase, SSH = sea surface height, Wtau = total wind stress, WtauAS = alongshore wind stress, MFAi = average MFA index, and Depth = average depth.

Sensitivity analyses

Error distribution, non-linearity

The final model was also estimated using a glm() implementation on untransformed catch rate data with the family option set to “Gamma(link="log")” to test an alternative error distribution to the Gaussian (Venables and Dichmont, 2004), namely the Gamma distribution which potentially is more flexible, though both implementations have variance being proportional to the square of the mean. Sensitivity to non-linearity in some of the continuous covariates was performed by addition of polynomial terms, as well as by examining for trend in residuals of models involving transformation of the covariates into categorical variables based on their 20% quantiles (Su et al., 2008). Partial residual plots were also examined as another test for signs of non-linearity.

Autocorrelation in the residuals – static comparisons

There was reasonable evidence of AR1 positive autocorrelation in the deviance residuals of the time-only model (Figure 2c). Addition of the covariates making up the final model resulted in a substantial reduction in the autocorrelation (Figure 2b), though with some autocorrelation persisting. In order to determine the extent to which parameter standard errors might have been compromised by unaccounted for autocorrelation (Figure 2b), a generalised least squares (gls) model was fit to the log-transformed catch rates with the same model terms as for the final model. The same fixed variance structure as per the final model was assumed but with a non-zero first-order autoregressive (AR1) autocorrelation structure fixed at a AR1 coefficient value (0.268) equal to the slope of a linear regression fit of final model residuals to the residuals at lag 1. The gls model was implemented using the gls() function in R package *nlme*, with correlation structure option of corAR1() and variance function option varFixed ().

Each of the combination of terms listed in Table 2 were tested for (each separately) retention in the final model according to the AICc criterion (via the “ML” estimation method). Also tested for were addition of main terms (each separately) to the final model of SSH, Wtau, WtauAS, and Depth.

Variance weight alteration − static comparisons

The aim of this sensitivity analysis was to assess how the power function modification of daily potlift count affects AICc, adjR^2, difference between sensitivity model’s adjR^2 and time-only (Sn+Mn+Sn:Mn) adjR^2, named adjR^2diff, and coefAR1, and residual diagnostic plots. Model m = 1 represents raw (unmodified) weighting by potlift count, and m = 8 approaches (though not quite equals) the no weighting scenario.

Model decision statistics and the AR1 autocorrelation coefficient (coefAR1) of deviance residuals were calculated for each of several glm models, differing in the values of m defining the modification to potlifts in regression weighting, namely $\omega_t = (\text{pots-lifted-on-day-t})^{1/m}$ ($m \geq 1$).

Estimation of variance weights and autocorrelation in the errors

To examine effects of estimating both autocorrelation and strength of variance weighting on the modelling results a generalized least squares model, with a given form of covariance structure and variance function, was implemented using the gls() function.

Two models were compared both of which involved the same linear predictor terms as in the accepted final model except for exclusion in both models of Sn:Mn. One model was otherwise equal to the final glm model (implemented equivalently via gls() with 0 autocorrelation and fixed (m=3) variance weight values, named “glm” here). The other model was estimated by gls with variance weighting function and residual autocorrelation estimated (via the “REML” estimation method), and the R variance function used was varPower() and correlation structure corAR1().

The Sn:Mn interaction term had to be excluded since, on account of the imbalance in sample size involving missing data for some season-month combinations, the gls() function could not calculate successfully (non-positive definite approximate variance-covariance matrix).

Spatially-specific temperature logger sub-models

Bottom temperature is the environmental variable most likely to vary across the fishing region, and it was of interest to determine if any relationship between log-transformed catch rate and bottom temperature varies at the finer scale of MFA block. For this purpose data from two additional bottom temperature loggers situated off Robe and Port Macdonnell were utilised. These loggers were at a similar depth to the Southend logger but involved sparser time series data. Three regression sub-models were examined, each consisting of log-transformed catch rate data and bottom temperature data specific to just one MFA block (55, 56, and 58), involving Southend, Robe, or Port Macdonnell bottom temperature loggers. These models only involved terms for time and the local bottom temperature (i.e. Sn+Mn+Sn:Mn+T).

Spatial-depth-fisher conditioned data sub-models

The effects on modelling outcomes of heterogeneity in catch rate data across MFA block, inshore-offshore depth zone, and fisher performance levels were examined by running the final regression model on each of three types of restricted data sets.

One set of models were run as per the final glm model but separately on three data sets each consisting of fisher catch and effort data aggregated to one MFA block (55, 56, or 58). Note that the MFAi term naturally was superfluous and hence was excluded. Another model involved the final glm model fit to fisher catch and effort data aggregated over depths <40 m deep and which was contrasted with another model fit to data aggregated over depths ≥40 m depths.

The final model was also applied to data for: (a) the top (by total catch rate over period 1994−2008) 50% of fishers, and (b) the remaining fishers to help gain an understanding of the effect of fisher skill on factors influencing catchability. The data set was further restricted for this analysis to MFA 56 and depth <40 m to avoid confounding from apparent spatial heterogeneity between the two skill-based data sets.

Moon phase sub-models

Two additional covariate data sources were obtained from BoM for the purpose of testing for confirmation of extrinsic stimuli explanations for the moon phase effect. One test involved addition (including interaction with moon phase) to the final model of cloud cover data consisting of an 8 level categorisation of amount of sky obscured by clouds. In order to examine the tidal nature of moon phase, a different test was run using tidal data (observed sea level in metres above Tide Gauge Zero), including both daily peaks and low-high differences, to substitute for moon phase.

Inference on catch rates

In order to obtain a measure of the impact on (non-transformed) catch rates due to individual covariates, the estimated mean catch rate plus confidence and prediction intervals were calculated. Consider a comparison, for a given day *t*, between two catch rate model scenarios, namely u_t and u'_t, that differ in their means through only covariate, $X_{t,i}$, which increases by an amount equal to its' interquartile range (IQR), that is, $X'_{t,i} = X_{t,i} + IQR_i$. Given that the IQR is a relative measure of variability it provides a basis for comparing impacts on catch rate by different covariates. Confidence intervals for the above two scenarios on the ratio of the mean catch rates, $E(u'_t)/E(u_t)$, are considered assuming the same level of fishing effort (i.e. daily potlifts) for both scenarios, so that $\sigma_t^2 = \sigma'^2_t$.

Then $E(u'_t)/E(u_t) = \exp(IQR_i * \beta_i)$, with confidence interval equal to

$$\exp(IQR_i * \beta_i \pm t(\alpha/2, n-k) * SE(\beta_i) * IQR_i), \tag{5}$$

where *n* = number of days, k = number of parameters, t() is the t-statistic, α is the significance level, and n−k is the degrees of freedom.

Prediction intervals for the same situation as for the confidence interval above, are obtained by considering the uncertainty on u'_t/u_t which is the ratio of the individual random daily catch rates for the two scenarios considered.

But $u'_t/u_t = \exp(\mu'_t + e'_t)/\exp(\mu_t + e_t) = \exp(IQR_i * \beta_i + e'_t - e_t)$, the variance of $\log(u'_t/u_t)$ equals $(IQR_i)^2 * (SE(\beta_i))^2 + \sigma'^2_t + \sigma_t^2$, and since e_t, e'_t and β_i are all normally distributed, then the 95% prediction interval for u'_t/u_t is

$$\exp(IQR_i * \beta_i \pm t(\alpha/2, n-k) * \sqrt{(IQR_i)^2 * (SE(\beta_i))^2 + 2 * \sigma_t^2}), \tag{6}$$

since the logarithm is a monotonic function. In order to calculate this prediction interval a given level of fishing effort needs to be provided to obtain a value for σ_t via application of regression weights (see supplementary data). Note that, for a given random day *t*, σ_t^2 can vary from σ^2 by as much as 75% to 250% (Figure S1, *m* = 3) due to variation in daily fishing effort, which can substantially change the width of prediction intervals. In the Results section median fishing effort of 7,000 potlifts was assumed.

Although IQR will vary between levels of a categorical covariate (e.g. temperature between fishing seasons), the same IQR was used across different levels due to sampling imbalance across fishing seasons and months (Table 1).

The total effect of a covariate that involves a time interaction was calculated by adding the estimate of the covariate main effect to the interaction term. For example, Sn:T quantifies the additive difference in the T slope coefficient across fishing seasons relative to 1998 with T+Sn:T being the total effect of temperature on mean log-transformed catch rate in season Sn. The standard errors for T+Sn:T were calculated taking into account that the regression parameters are correlated among themselves (e.g. covariance between T and Sn:T). Similarly, Mn:WaveH adds to WaveH relative to month 1.

Results

Final model structure

The final model (Equation 7) did not include the main terms wind, SSH, depth, and all interactions except for the month interaction with wave height and the fishing season interaction with bottom temperature. The only lagged covariate term selected was a moving average for wave height over a lag period involving the last three days (WaveHLagAvg). All retained terms were also highly statistically significant. The total number of estimated parameters was 72.

$$\mu_t = \mathrm{Sn} + \mathrm{Mn} + \mathrm{Sn} : \mathrm{Mn} + \mathrm{WaveH} + \mathrm{WaveP} + \mathrm{T} + \mathrm{Moon} + \mathrm{MFAi} + \mathrm{Mn} : \mathrm{WaveH} + \mathrm{Sn} : \mathrm{T} + \mathrm{WaveHLagAvg}\,. \quad (7)$$

There were no outliers, influential data points, violations of mean-variance homogeneity, non-normality, or high collinearity among covariates. No strong non-linearity was identified in the response of log-transformed catch rates for any of the covariates. The Gamma GLM (for both log and inverse link functions) provided similar results to the log-normal implementation. Autocorrelation in the deviance residuals was substantially reduced (Figure 2b,2c), but some residual autocorrelation persisted and possible effects of this are examined in the sensitivity analyses.

Final model terms

Each row in Table 2 provides statistics comparing a model that differs from the final model only by omission of the regression term indicated, and it indicates that all listed combinations of covariate terms were strongly supported according to the model decision statistics. The proportion of total variance in log-transformed catch rates explained by all the terms (including time) in the final weighted regression model was 91.3%. Exclusion from the final model of all the covariate data combined, resulted in a loss of 7.0% explained variance (adjR^2), leaving 84.3% of total variance attributable to the time trend. Exclusion of all the wave covariates (height and period) clearly indicated that these were the most important environmental covariates explaining in total 2.5% of variance. Similarly 0.9%, 1%, and 1.3% of variance was explained by each of moon phase, temperature, and MFAi respectively.

The confidence intervals (CI) and prediction intervals (I) are provided in Table 3 for a day with 7,000 potlifts representing median fishing effort among days. The largest effect of same day wave height was during month 8 when a 1.1 m increase in same day wave height resulted in a reduction to μ_t of 14% (95% CI −18% to −10%). Note that month 8 is only informed by the more recent fishing seasons (Table 1). Impacts during months 1 and 2 were much less and CVs indicate high relative uncertainty. IQR does not vary much between the months and suggests an increase in wave height of 1.1 m (used for each month) is reasonably representative for any of the months. The prediction intervals are substantially wider than the confidence intervals and reflect high overall daily noise (at 7,000 potlifts). For example, the 95% prediction interval for the relative change in catch rate for an increase in wave height of 1.1 m was estimated to be −39% and +20% about the mean daily catch rate during month 8 for a day during which 7,000 potlifts were hauled (Table 3).

Wave period was estimated with a positive coefficient; μ_t increases by 7% (95% CI 6% to 8%) for an increase of 1.9 seconds. The corresponding predicted catch rate change for a random day is highly variable (95% PI −24% to +49%; Table 3). The wave period and height data were only slightly-moderately correlated (< 0.35) but WaveP appears to moderate the effect of WaveH on lobster catch rates. Results shown in both Tables 2 and 3 suggest WaveH to be a stronger main effect than WaveP, though model selection clearly suggests both covariates help explain the data.

The coefficient for WaveHLagAvg is positive which means that the larger the average swell over the last three days, the larger the estimated mean catch rates for today. The confidence interval conveys this with a relatively small, 5% (95% CI 4% to 6%), increase in μ_t with an increase of 1.0 m in average lagged wave height, and prediction interval ranging from −25% to +46% (Table 3). Model sensitivity testing on the form of the lagged wave height terms, using AICc and adjR^2 as model selection guides, resulted in 3 and 4 days lag being determined optimal (AICc values too close to separate models) with averages over shorter or longer lag periods being increasingly less desirable (Figure 3). Similarly, models involving a distributed lag combination of individual terms for each of the days in the lag averaging period were found to be less appropriate than the lag 3 moving average model (results not shown).

The effect of an increase in temperature was to decrease μ_t for all seasons. For example, a change of 2.2°C during fishing season 2000 was expected to decrease μ_t by 14% (95% CI −17% to −11%; 95% PI −39% to +29%) (Table 3). Temperature effects vary considerably among fishing seasons. This could reflect real heterogeneity, though causal attribution of this to catchability alone is tenuous (see supplementary data). Also, IQR varies substantially among fishing seasons implying that a change in temperature of 2.2°C is not equally likely for all seasons. The temperature effect in the modelling accounts for seasonality explicitly by incorporating monthly categorical time variables. The temperature increases apply uniformly across months which is okay given month is explicit as a time factor in the model, and the Temperature : Month interaction term was not retained by model selection.

The estimated effect of a change in moon phase on mean catch rates is approximately cyclic, increasing up to and including the phase prior to the full moon, at which a 10% increase on the new moon mean catch rates is achieved. After full moon, mean catch rates decrease steadily to less than 5% below the new moon levels for phases between the full and new moons. The predicted change in catch rates on a random day is typically much wider as illustrated in Figure 4 The spatial index covariate, MFAi, was estimated with a negative coefficient reflecting higher catch rates further north along the Bonney Coast.

Model structure sensitivity

Autocorrelation in the residuals − static comparisons

The generalised least squares model with fixed variance structure and fixed non-zero autocorrelation (see Methods) found that although, as expected, the standard errors for most parameters did increase, it was not substantial (5% to 20%). Similarly, there were no substantial impacts on approximate 95% confidence intervals of parameters (results not shown).

The same combinations of final model terms as listed in Table 2 were also found to be retained according to AICc for the gls model version. Also, the addition of main terms (each separately) SSH, Wtau, WtauAS, and Depth closely paralleled results of doing this with the final glm model according to AICc differences (results not shown). In the (Gaussian) glm model, these were among the terms subsequently deleted via the adjR^2 criterion during backwards model selection. Use of this criterion is not applicable for a gls as it confounds with the random effects component (and it does not equal the proportion of total variation in the dependent variable accounted for by covariates, nor is it bounded between 0 and 1).

Variance weight alteration − static comparisons

Figure 5 shows that less weighting (greater *m*) provides for models with lower adjR^2 but with a larger proportion of this being explained by the environmental covariates. Figure 6 indicates that AICc was at a minimum around *m* = 1.75, below which it rose sharply and above which it increased at a slower rate. The AICc for *m* = 3 was 66 units lower than for *m* = 1 (maximum weighting by potlifts) and 204 units lower than for *m* = 8 (low weighting). *m* = 3 involved the best QQ residual plot (results not shown) among the spread of *m* values tested. Also, *m* = 1.75 had lower proportion variance explained by environmental covariates (Figure 5) and slightly higher residual autocorrelation (Figure 6) than *m* = 3, the latter reducing with increasing *m* (Figure 6).

Estimation of variance weights and autocorrelation in the errors

The gls had a much lower AICc than the glm. An exponent was estimated for the power function for variance weight that was nearly equal to the m = 1.75 value found in the previous section's analysis involving sensitivity to static variance weights. No gls estimated coefficient parameters (of ones with 95% confidence intervals excluding 0) were strongly (< 15%) affected in values. The exception involved parameters for moon phases 6 and 7 which for the gls involved less large negative values. Similarly, the 95% confidence interval for the levels of Sn:T included 0, but this was also observed in the for the glm version of the model. The effect of positive autocorrelation was an increase in parameter standard errors as expected. Such changes were generally < 25% in magnitude resulting in only minor changes in 95% confidence intervals.

Note that the model without Sn:Mn is qualitatively similar (sign and magnitude of parameters) to the final model, though is less well time-detrended which increases residual autocorrelation. The ACF plot of deviance residuals was visually less superior when Sn:Mn was removed in the glm() function implementation (results not shown). This means that the outcomes of this sensitivity analysis contrasting gls and glm were potentially more pronounced to the extent of the increase in the autocorrelation.

Spatially-specific temperature logger sub-models

For each of the three pairs of temperature logger MFA data sets the same qualitative result was obtained, namely a substantial (AICc reductions from time-only models of 12, 112, and 33 respectively for MFAs 55, 56, and 58) negative temperature effect was estimated between catch rates and local bottom temperature.

Temperature coefficients (with CV and data IQR) for each of Robe, Southend, and Port Macdonnell loggers were respectively −0.04 (0.27,1.7), −0.07 (0.09,1.7), and −0.07 (0.17,2.4).

Spatial-depth-fisher conditioned data sub-models

For the final model run on each of the MFA-specific catch rate data, (but using the same covariate data set as per the whole-zone model), the main outcome was no substantial differences between MFAs, except for WaveH+Mn:WaveH. All effects in all MFAs substantially worsened AICc when excluded from the model with the differences in adjR^2 relative to the time-only models being 4.3%, 3.8%, and 6.7% for MFAs 55, 56, and 58 respectively. The strongest effect difference between MFAs was found for wave height. For each MFA, the estimated effect of WaveH+Mn:WaveH was weaker for months 1 and 2 than for months 3 to 8, but interestingly, in each month the magnitude (results not shown) of estimated negative effects was strongest in MFA 58 and weakest in MFA 55. Similarly, changes in adjR^2 (and AICc) resulting from excluding WaveH+Mn:WaveH were 0.9% (76), 1.0% (109), and 3.2% (312) for MFA 55, 56, and 58 respectively. T+Sn:T effects were substantially negative in all seasons and across MFAs, but were somewhat smaller (results not shown) in MFA 55 The adjR^2 (and AICc) impacts of dropping temperature were 0.6% (50), 0.9% (98), and 1.0% (94) for MFAs 55, 56, and 58 respectively. These results confirm those from sensitivity modelling involving spatially-specific temperature loggers.

Models applied separately to inshore (<40 m depth) and offshore (≥40 m depth) data experienced worsened AICc values for all effects when these were excluded from the model, except for term MFAi inshore which involved a decrease (i.e. improvement) in AICc by 2.2 when excluded (compared to an increase of 160 for offshore). Differences in adjR^2 relative to time-only models were similar between inshore (7.6%) and offshore(7.0%), which is similar to the whole-zone result of 7.0% as were the sign and season-month patterns of estimated effects. However, apart from MFAi not being supported inshore, another major difference between inshore and offshore results was that WaveHLagAvg, and particularly WaveH+Mn:WaveH, were weaker offshore. Changes in adjR^2 (and AICc) resulting from excluding WaveH+Mn:WaveH were 3.4% (329) for inshore and 0.2% (7) for offshore, and similarly for WaveHLagAvg 1.1% (123) inshore and 0.2% (18) offshore.

The results of restricting data to inshore MFA 56 and either fishers belonging to the top or the bottom 50% catch rate group indicated no major differences to the group combining all fishers for inshore MFA 56. However Sn:T was weaker (AICc differences < 2 when excluded), but was so for both groups of fishers.

Moon phase sub-models

The result of adding cloud cover as a covariate to the final model increased AICc by 6.4 units and contributed only 0.02% adjR^2. Subsequent addition of an interaction term between moon phase and cloud cover gave an even less substantial result. Similarly, excluding moon phase from the final model and adding either peak tide or high-low tidal differences resulted in a model substantially less well supported with the AICc over 100 units larger than that for the final model.

Discussion

General

This study has identified several environmental variables which impact on the catch rates of J. edwardsii within the Southern Zone rock lobster fishery of South Australia. These variables are wave height and period, lagged wave height, bottom temperature, and moon phase. Given the specified regression weighting by potlifts, these variables, together with a spatial index, explained 7.0% of total variance in log-transformed daily catch rates. Another 84.3% was explained by a month and season time trend. Similar results were observed in Victoria (see supplementary data).

Wave height and period

Both a negative effect on catch rates by same day wave height and a positive effect by wave heights over the previous three day period were observed. Srisurichan et al. (2005) reported similar results for the western rock lobster *P. cygnus* concerning a positive response of legal-sized catch rate to lagged wave heights from days prior to fishing. It was suggested that the swell provided greater protection from predators by increasing bottom turbidity and food availability, presuming this to apply over a few days. Weissburg and Zimmer-Faust (1993) found that for blue crabs (*Callinectes sapidus*) slow-flowing water was optimal for predation, and Factor (1995) suggested that turbulence and greater fluid velocities may make it harder for crustaceans to follow bait odour trails. On the day of fishing, turbulent conditions could reduce feeding ability, and hence partially explain the negative effect by wave height on same-day catch rates found in the present study.

Sensitivity analyses involving separate modelling of inshore and offshore found the wave height effect (both same-day and lagged) to be notably stronger inshore than offshore. In addition, effects were stronger further south along the coast. These results may relate to increased bottom turbulence in the shallower inshore waters as well as in the narrower southern continental shelf regions (from 28 km in the south to 60 km off Robe in the north (Lewis, 1981b)).

A positive catch rate response to increased same-day wave period was found. While unclear perhaps one contributing factor for this result is that of potentially reduced turbulence, for a given wave height, when waves pass less frequently (longer periods) resulting in less interference to fishers and lobsters.

The negative effect on catch rates of same-day wave height is substantially less in months 1 (October) and 2 (November). The reason for this is not clear. However, it is known that males moult between October and November (MacDiarmid, 1989) during which time they are highly reclusive (Lewis, 1981a) thus lessening the relevance of turbulence as a curtailer of effective foraging. Attribution of this monthly heterogeneity (Mn:WaveH) to catchability alone is tenuous and confounding where changes in lobster abundance might exist (see supplementary data).

Temperature

Bottom temperature was found to have a negative effect on catch rate, regardless of month or season. This included cold-water upwelling events where extreme between-day temperature drops were evident (supplementary data, Figure S3). Sensitivity analyses indicated no substantial spatial heterogeneity in the results. This finding is contrary to a number of studies in the literature on lobsters which found a positive association between catch rate and temperature, (McCleese and Wilder, 1958; Morgan, 1974; Smith et al., 1999; Ziegler et al., 2004; Drinkwater et al., 2006; Schmalenbach, 2009). However, Courchene and Stokesbury (2011) did report a negative association between *H. americanus* catch rates and bottom temperature, suggesting it was due to a negative relationship between catchability and temperature. Specifically, the authors surmised that lobster mobility is reduced at higher temperatures and considered that increased lobster growth rates at such temperatures may result in avoidance of traps by moulting lobsters. However, in the present study of *J. edwardsii,* a negative temperature coefficient was found to apply for all months, including non-moulting periods. In addition, catch rates were observed to decline over quite a large temperature range from 12−17°C, though this is confounded by time and other covariates (supplementary data, Figure S2).

One potential explanatory mechanism involves the oxygen-based metabolic concept known as the aerobic scope for activity (SFA) which expresses the relationship between active and standard respiratory consumption of an animal (Crear and Forteath, 2000). SFA, as a physiological measure of spare capacity to do sustained work, suggests a potential influence on catch rates via dependence of SFA on ambient bottom temperature. For laboratory held intermoult *J. edwardsii,* the SFA was reported by Crear and Forteath (2000) as a downward curving function of temperature peaking about 13°C (acclimatised temperature over 36 hours), dropping off well within suggested lethal limits of 5°C to 21°C. Recorded bottom temperatures (results not shown) off Southend (60 m depth) generally ranged within 9°C and 18°C and exhibited temperature gradients of up to 4°C within a week, (median 14.5°C). Preferred temperatures may be lower for crustaceans living in lower ambient temperatures and be more clearly defined in temperature gradients, frequently involving near maximum scope for activity (Lagerspetz and Vainio, 2006). Assuming that the preferred temperature is at or below 13°C, then the SFA curve at ambient temperatures above 13°C may be shaped lower above those temperatures than below them, the aggregate effect of which could mean declining catch rate above 13°C. SFA impacts on animal motor performance and behaviour, may differ between species and within species spatially (Crear and Forteath, 2000; Drinkwater et al., 2010).

Alternatively, bottom temperature could act as a proxy index for another (unmeasured) variable impacting on catch rates. From October to May changes in bottom temperature in the Bonney Coast region are linked in a complex and dynamic manner with changes in other variables such as current velocity (Schahinger, 1987), salinity, dissolved oxygen and nitrate concentrations (Lewis, 1981b). All of these variables have the ability to impact on lobster catchability or activity (Morgan, 1974; Factor 1995; Zimmer-Faust, et al., 1984; Crear and Forteath, 2000).

Moon phase

During the period just prior to the full moon rock lobster catch rates were highest, with lowest catch rates observed prior to the new moon. The finding that lobster catch rates are affected by moon phase is substantiated in the literature for other species (Morgan, 1974; Yamakawa et al., 1994, Srisurichan et al., 2005), though these involved peak catch rates around the new moon. There exist studies on catch rates of other crustacea that do indicate the same timing in relation to moon phase found in the present study. For example, Courtney et al. (1996) working on Eastern King Prawns (*Penaeus plebejus*) found that catch rates peaked shortly before the full moon and declined for about seven days afterwards, especially for males implicating potential sex-specific factors.

Results from sensitivity analyses indicated no substantial support (AICc criterion) for cloud cover being added to the final model. This was also true for tide readings when substituted for moon phase. Models fit separately for inshore-offshore returned the same result for moon phase, and this was also reported by Morgan (1974). In terms of nightly movement activity of *J. edwardsii*, MacDiarmid et al. (1991) found no significant correlation between the proportion of lobsters active at night in New Zealand and the number of hours of moonlight. Similarly, Williams and Dean (1989) reported no increase in the length of the lobster active period when hours of darkness in summer were increased to match the winter length of darkness. This agrees with the findings of the present study which highlighted that the period prior to the full moon, as opposed to during it, experiences maximum catch rates. Overall, these findings suggest that moon phase effect on catch rates is likely to involve more than a direct response to moon light levels alone, such as an endogenous timing system (Williams and Dean, 1989).

Modelling

Table S1 provides an overview of the variety of models used in this study. One suite of models was designed to explore potential spatial, depth, or fisher heterogeneity of environmental effects.

Catch rate data restricted to either MFA block or inshore-offshore region produced similar regression results for temperature, moon phase, and wave period. For these environmental variables the results obtained using the whole-zone final models are likely to reflect catch rate response throughout the fishing region. A smaller, though still substantially negative, temperature effect was detected for MFA 55, both from a model using temperature data more local to MFA 55 (off Robe) as well as from the full final model fit (which uses Southend logger temperatures). The reason for this is not clear, however, within MFA 55 fishing is spread over a wider area (results not shown) compared to MFAs 56 and 58. As a result, catch rate data aggregated across MFA 55 may involve pots exhibiting greater variation in actual local temperatures. However, for wave height, substantial spatial differences were detected in the inshore-offshore and MFA sensitivity analyses (discussed under wave height).

The inshore-offshore analysis revealed that inshore the spatial covariate (MFAi) effect was weakly supported; indicating little impact due to location fished <40 m deep along the coast. This outcome is not related to known spatial trends in mean lobster weight (increases further north, McGarvey et al., 1999), since exploratory data analysis (results not shown) provided little indication of weaker north-south mean weight trends inshore compared to offshore. An alternative explanation is that the number of lobsters offshore is greater further north-west, and that inshore there is a more uniform spatial spread. Evidence for this comes from spatial mapping of legal-sized lobsters caught as part of fishery independent monitoring surveys (FIMS) in the region (Linnane et al., 2011a,b). Prior knowledge of how catch rates, mean weight, and growth vary in the Southern Zone confirm that a gradient from south to north is well supported. In particular, the southern areas have much slower growth, and smaller lobsters generally, and these factors increase monotonically as location shifts northward in the Southern Zone.

Running a regression on data restricted to top-bottom 50% fisher groups (according to long-term catch rates) fishing inshore within MFA 56 revealed that the higher performing half of the fishers did not respond substantially differently to any of the environmental conditions than the lower performing group of fishers. However, this does not necessarily mean that the time index component (Sn+Mn+Sn:Mn), often assumed to be an index of relative abundance, is unaffected by changing fisher composition in the fishery over time.

Other models in the sensitivity analyses were designed to examine the response of the final model to violations in regression assumptions. The reported adjR^2 statistic is probably inflated somewhat (Willett and Singer, 1988), due to data noise reduction via variance weighting influencing the model fit in addition to information from the linear predictor covariates. However, the results of the sensitivity analyses on variance weight alteration (Figure 5) indicated that the increase in adjR^2 between the final model (m = 3) and a weakly-weighted version of the final model (m = 8) was relatively small (0.913−0.898=0.015).

More generally Figure 5 shows that less variance weighting provides for models with lower adjR^2 but with a larger amount being explained by the environmental covariates. This may be because weighting de-emphasises less precise data points, which in turn reduces residual variability that could otherwise be explained by model covariate terms. Figure 6 also shows that autocorrelation in (deviance) residuals reduces with less weighting which may be related to correspondingly reduced relative influence of daily potlifts and its' associated temporal autocorrelation (results not shown). This effect of autocorrelation in the daily potlift data can also be seen by comparing the ACF plots of the final model's response and deviance residuals (Figure 2a and b).

The existence of autocorrelation in the final model deviance residuals (AR1 coefficient of 0.268) did not appear to substantially impact model outcomes, as determined by a gls version of the final model with fixed variance weighting (m = 3) and fixed AR1(0.268) autocorrelation. When both autocorrelation and variance weight strength were estimated (using gls), for the final model without the term Sn:Mn, this also resulted in estimated model term parameters and standard errors that were inconsequentially impacted.

Implications

Overall, the outcome of a real but relatively small environmental impact on daily catchability suggest that the catch rate data is perhaps a reasonable index for relative abundance of *J. edwardsii* for SA's Southern Zone fishery (and similarly so for Western Victoria; see supplementary data, section Modelling of the Western Zone Victorian catch rates). According to the results, the data do not indicate that environmental variables examined by the present study were the likely cause, through daily environmental catchability, of major changes in catch rates such as the steep decline observed between seasons 2003 and 2009 (Linnane et al., 2011a). Comparison of a season-month catch rate data series with a version of "standardised" catch rate (supplementary data, Figure S4) visually illustrated the relatively minor impact of daily catchability; hence, with the latter unlikely to have an inadvertent influence on the setting of yearly TACC. However, a number of caveats should be highlighted as below.

1. Modelling did not explicitly incorporate influences such as changes in growth or fishing practice both of which remain implicitly expressed in the standardised catch rate.
2. Intrinsic ambiguity may exist in the interpretation of estimated time-covariate interaction effects (Maunder and Punt, 2004; Hinton and Maunder, 2004) in relation to catchability and abundance (see supplementary data).
3. The resolution of the data needs to be considered. Maunder and Punt (2004) note that at a coarser level of data aggregation the R^2 statistic is generally greater than at a finer resolution. Hence, if all data in this analysis had been monthly for example, instead of daily, the total variance in log-transformed daily catch rates explained by the environmental covariates could be higher with a correspondingly different outcome regarding the influence of catchability.

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Table 1. Number of days with geometric mean catch rate per fishing season and month, used in the modelling. Sn = season.

	Mn 1 (Oct)	Mn 2 (Nov)	Mn 3 (Dec)	Mn 4 (Jan)	Mn 5 (Feb)	Mn 6 (Mar)	Mn 7 (Apr)	Mn 8 (May)	Off-season (Jun-Sep)	All
Sn 1998	0	0	0	9: 1.1	28: 1.0	27: 1.0	30: 0.8	0	0	94: 0.9
Sn 1999	30: 1.4	30: 1.5	29: 1.5	0	27: 1.3	27: 1.2	14: 1.4	0	0	157: 1.4
Sn 2000	30: 1.5	30: 1.6	29: 1.6	31: 1.7	28: 1.4	26: 1.4	9: 1.7	0	0	183: 1.5
Sn 2001	26: 1.6	30: 1.7	29: 1.9	29: 2.0	27: 1.6	0	0	0	0	141: 1.8
Sn 2002	0	0	0	24: 2.3	28: 1.7	29: 2.0	22: 1.9	0	0	103: 1.9
Sn 2003	0	0	0	0	0	0	0	0	0	0
Sn 2004	0	0	0	0	0	0	0	0	0	0
Sn 2005	0	0	0	0	0	0	0	0	0	0
Sn 2006	27: 1.4	27: 1.3	30: 1.4	19: 1.4	0	0	0	0	0	103: 1.4
Sn 2007	28: 1.2	30: 1.1	31: 1.1	31: 1.3	29: 1.1	31: 0.9	30: 0.7	31: 0.5	0	241: 1.0
Sn 2008	30: 0.7	30: 0.8	31: 0.8	30: 0.9	25: 0.8	31: 0.7	28: 0.4	31: 0.4	0	236: 0.6
All	171: 1.2	177: 1.3	179: 1.3	173: 1.5	192: 1.2	171: 1.1	133: 0.9	62: 0.4	0	1258: 1.2

Table 2. Impact of excluding given combinations of terms from the final model.

Term excluded	Δ-AICc	Reduction in adjR^2	Estimated parameters	Anova_Pr(>F)
MFAi	-176.5	0.013	71	1.6E-38
Moon	-117.7	0.009	65	4.4E-24
Sn:T	-29.5	0.003	65	3.8E-07
T+Sn:T	-121.1	0.010	64	1.5E-24
WaveP	-175.3	0.013	71	2.8E-38
WaveHLagAvg	-65.7	0.005	71	1.2E-15
Mn:WaveH	-70.2	0.006	65	8.2E-15
WaveH+Mn:WaveH	-193.5	0.015	64	7.1E-39
WaveH+Mn:WaveH+WaveHLagAvg	-223.0	0.018	63	1.8E-44
WaveP + WaveH+Mn:WaveH+WaveHLagAvg	-303.6	0.025	62	2.7E-60
All covariate terms (time-only model)	-709.4	0.070	46	4.1E-137
None (final model)	0	0	72	-

Table 3. Coefficient estimates and coefficients of variation (CV) by time period. 95% confidence (C.I.) and prediction (P.I.) interval limits, for 1186 degrees of freedom, are on the scale of catch rates indicating impact of IQR increases in covariates. IQR column values in brackets refer to IQRs specific per time period but were not used in calculations. Regression weight assumed for the prediction intervals is based on median daily potlifts of 7,000.

Final model term	Estimate	CV	exp(IQR*Est.)	95% C.I. left	95% C.I. right	95% P.I. left	95% P.I. right	IQR
WaveH + Mn1:WaveH	-0.013	0.88	0.98	0.96	1.01	0.70	1.38	1.1 (1.1)
WaveH + Mn2:WaveH	0.010	1.27	1.01	0.98	1.04	0.72	1.41	1.1 (1.1)
WaveH + Mn3:WaveH	-0.094	0.14	0.90	0.87	0.93	0.64	1.26	1.1 (1.0)
WaveH + Mn4:WaveH	-0.094	0.14	0.90	0.87	0.93	0.64	1.26	1.1 (1.1)
WaveH + Mn5:WaveH	-0.089	0.16	0.90	0.88	0.93	0.65	1.26	1.1 (1.0)
WaveH + Mn6:WaveH	-0.059	0.23	0.94	0.91	0.96	0.67	1.31	1.1 (1.1)
WaveH + Mn7:WaveH	-0.097	0.15	0.89	0.87	0.92	0.64	1.25	1.1 (1.1)
WaveH + Mn8:WaveH	-0.133	0.16	0.86	0.82	0.90	0.61	1.20	1.1 (1.3)
T + Sn1998:T	-0.101	0.18	0.80	0.74	0.86	0.57	1.25	2.2 (2.2)
T + Sn1999:T	-0.020	0.61	0.96	0.91	1.01	0.68	1.37	2.2 (1.6)
T + Sn2000:T	-0.069	0.13	0.86	0.83	0.89	0.61	1.29	2.2 (2.0)
T + Sn2001:T	-0.021	0.51	0.95	0.91	1.00	0.68	1.37	2.2 (1.9)
T + Sn2002:T	-0.123	0.21	0.76	0.68	0.85	0.54	1.24	2.2 (0.6)
T + Sn2006:T	-0.090	0.26	0.82	0.74	0.91	0.58	1.28	2.2 (1.3)
T + Sn2007:T	-0.038	0.33	0.92	0.87	0.97	0.66	1.34	2.2 (2.5)
T + Sn2008:T	-0.027	0.34	0.94	0.90	0.98	0.67	1.36	2.2 (2.2)
WaveHLagAvg	0.045	0.12	1.05	1.04	1.06	0.75	1.46	1.0
WaveP	0.035	0.07	1.07	1.06	1.08	0.76	1.49	1.9
MFAi	-0.250	0.07	0.95	0.94	0.95	0.68	1.32	0.2

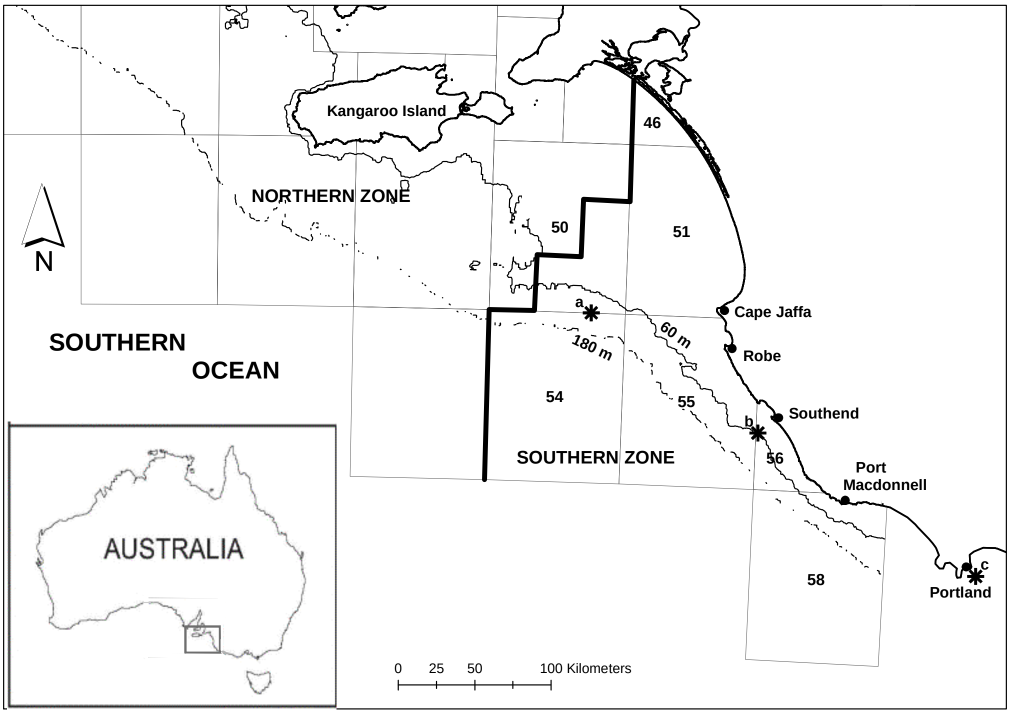

Figure 1. Northern and Southern Zone rock lobster fisheries of South Australia. Numbered boxes represent Marine Fishing Areas (MFAs). Three sources of environmental data are indicated, namely "a" for waves, "b" for bottom temperature, and "c" for sea surface height (SSH) and wind.

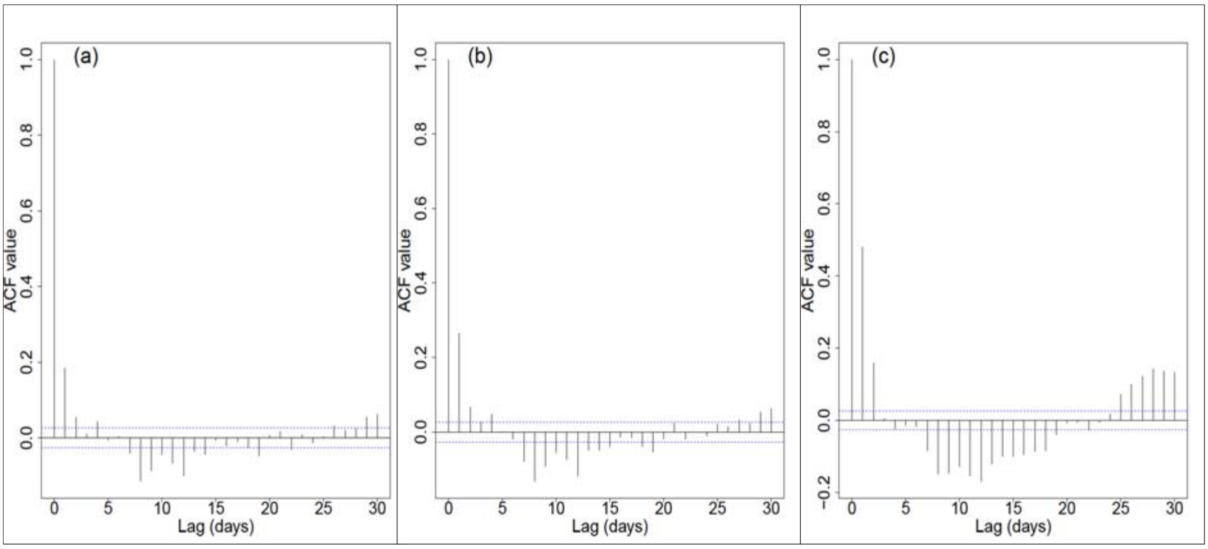

Figure 2. Autocorrelation function plots (ACF) of (a) response, and (b) deviance residuals of the final model, and (c) deviance residuals of the time-only model over 30 days.

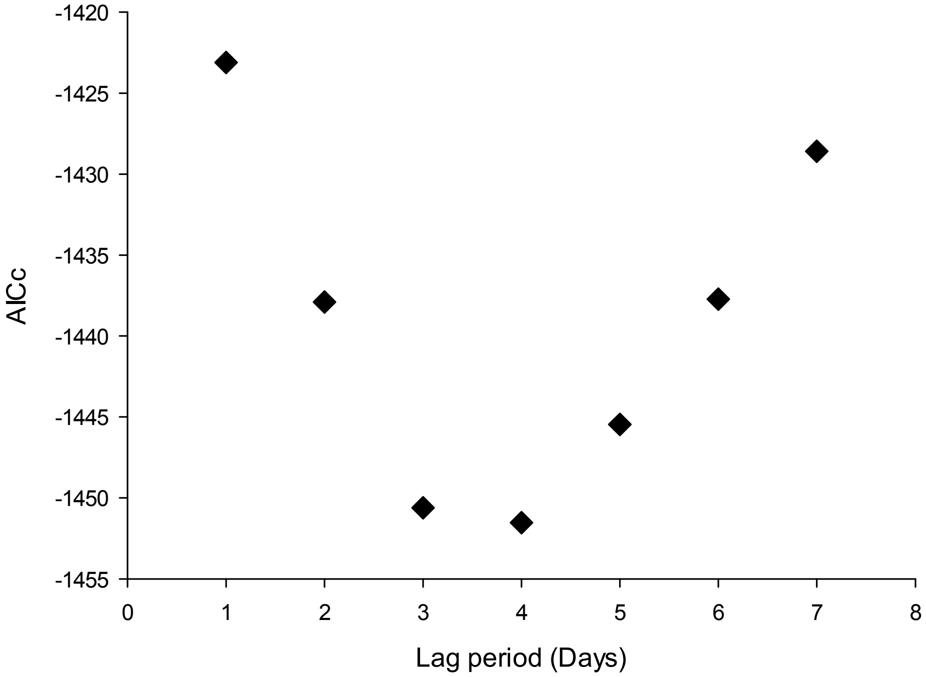

Figure 3. Aikaike Information Criterion (AICc; small sample corrected) for measuring model fit under different choices of lag between wave height and daily catch rate. Best fits, as lowest AICc, were observed for the 3 and 4 day lags. Thus, higher catch rates followed days of stronger swell by about 3 or 4 days.

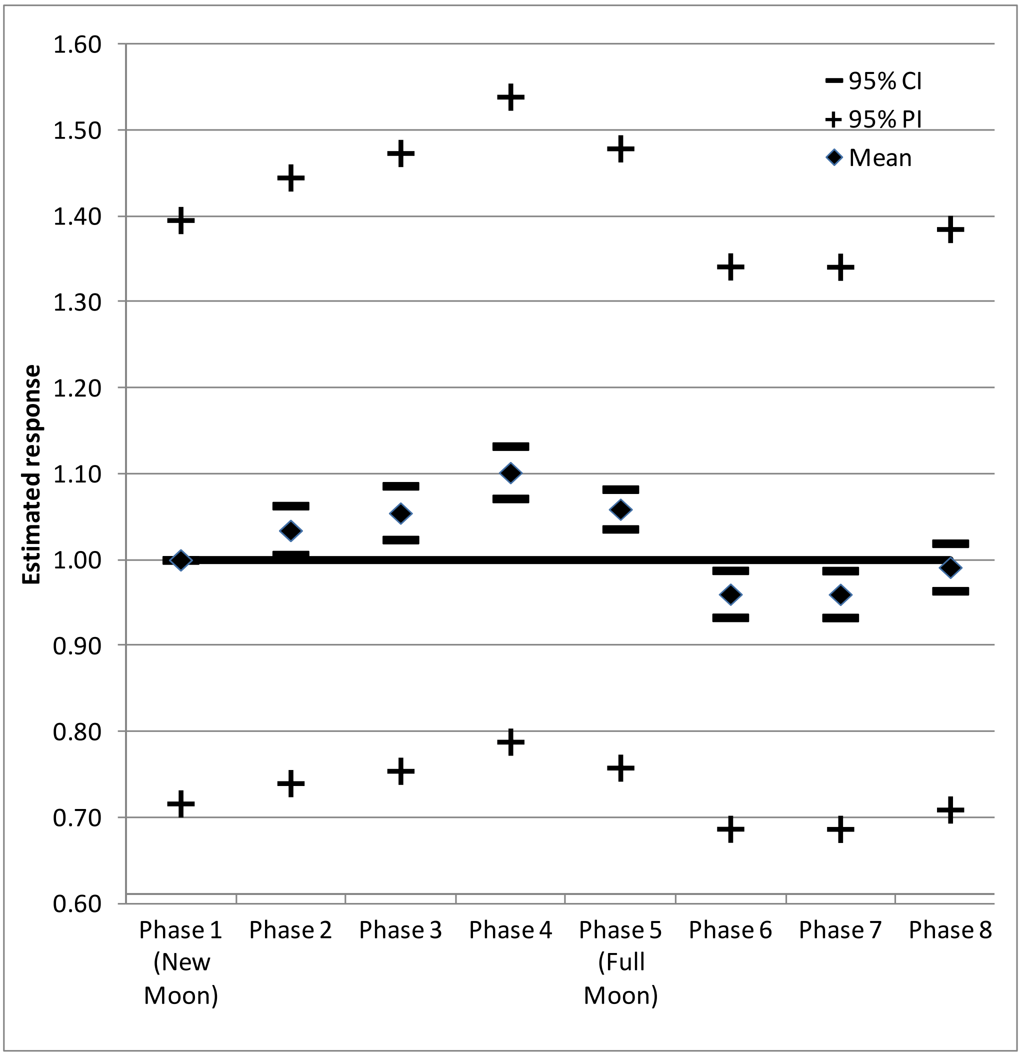

Figure 4. Estimated mean (relative to the new moon) catch rate response by moon phase and the 95% confidence and prediction intervals.

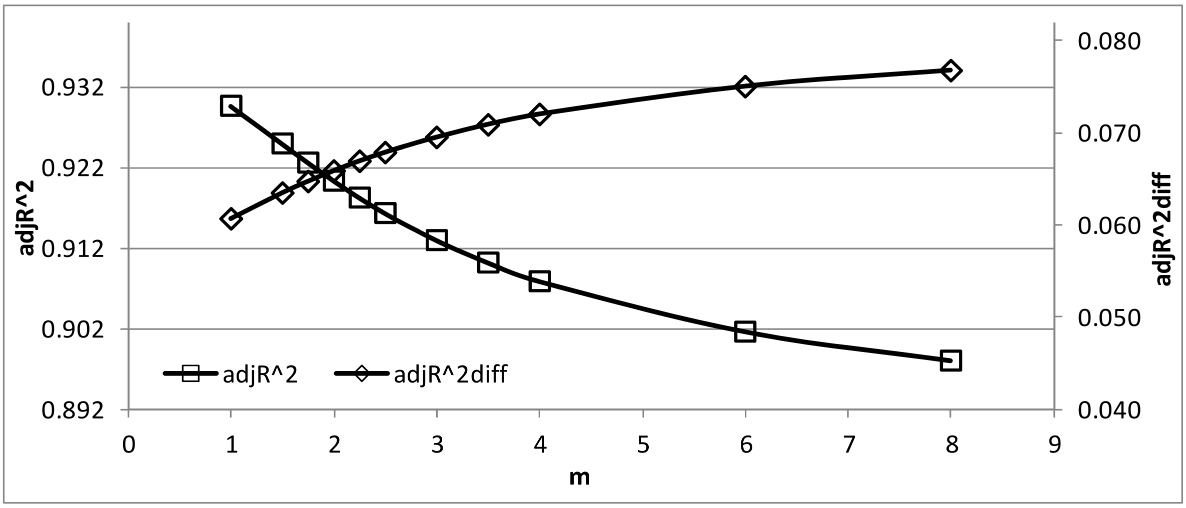

Figure 5. Adjusted proportion variance and the difference between the variation explained by models with and without environmental covariates, as a function of "m".

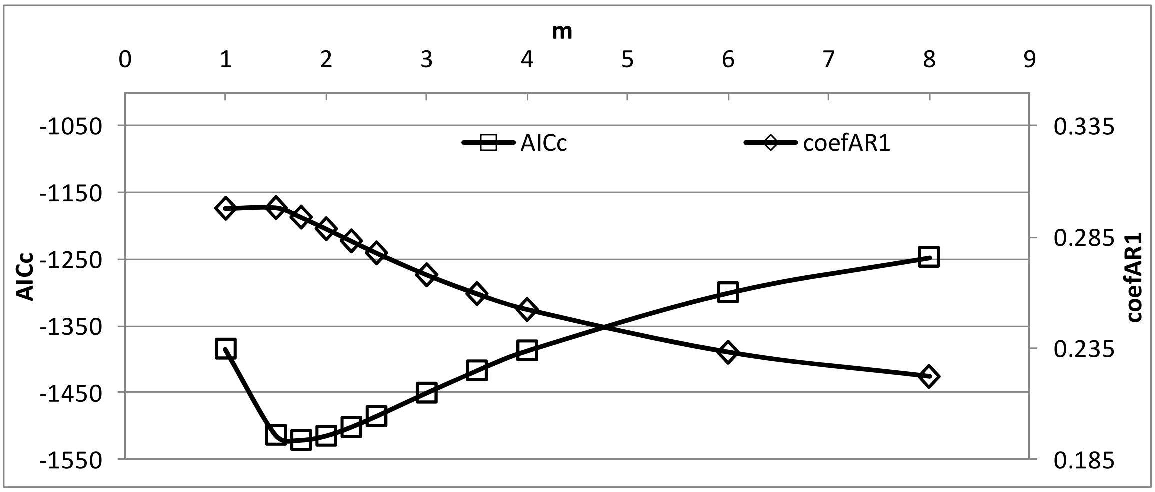

Figure 6. AICc and AR1 correlation coefficient as a function of "m".

Supplementary data

Regression weights

Motivation

The unweighted glm regression model of the log-transformed catch rates produced square-root-standardised deviance residuals with no pattern against predicted values. However the QQ-plot of the standardised deviance residuals showed these to be excessively left-skewed. Examination revealed that this was principally due to days with less than 200 potlifts. The 25%, 50%, and 75% percentiles of the daily potlifts data equal around 2,400, 6,700, and 10,000 respectively suggesting considerable variability in amount of effort between days. The plot of residuals versus potlifts before weighting showed clearly larger dispersion at the lower end of the daily fishing effort range rapidly diminishing from 100 to about 2000 potlifts and stabilising for larger fishing effort.

$Var(U_t)$ − Information in daily potlifts

The daily regression weights (ω_t) are used to account for higher levels of precision when sample sizes (potlifts) are higher. Larger values of ω_t result in lower applied variance hence resulting in variance for different days no longer being constant but equalling $\sigma^2/\omega_t = \sigma_t^2$ for day *t* where σ^2 is the regression estimated variance parameter for the distribution of the log-transformed catch rates.

A datum of catch rate for day t, U_t, equals the sum of all lobster weight caught by L_t fishers divided by the total number of pots set that day,

$$U_t = \sum_{l=1}^{L_t}\sum_{p=1}^{P_{t,l}} C_{t,l,p} / \sum_{l=1}^{L_t} P_{t,l} \ , \tag{S1}$$

where fisher *l* fished with $P_{t,l}$ pots and pot *p* caught $C_{t,l,p}$ kg of lobster.

If all the pots and lobsters were independently and identically distributed (i.i.d) then U_t, when considered as a large-sample mean lobster weight conditioned on a given number of potlifts on day t, has variance:

$$Var(U_t) = S^2 / P_t \tag{S2}$$

where $S^2 = Var(C_{t,l,p})$ is the population variance of lobster catch weight per individual pot across the population of sampling units of location-fisher-pot in the fishery and $P_t = \sum_{i=1}^{L_t} P_{t,1}$. In this case $\omega_t = P_t$ is reasonable and states that as P_t increases the precision on U_t increases along with its influence in model estimation. Note that the population of location-fisher-pot units is so large that on any given day this population is effectively infinite and hence finite population considerations are not an issue.

$Var(U_t)$ − Power function of daily potlifts

The above mentioned i.i.d. assumption is likely to be violated on any day since pots are clustered by fisher, the effect of which depends on how much fisher skill varies and on fishing location heterogeneity. There is also spatial autocorrelation that may reasonably be assumed positive (so pots spatially closer have more similar catch) which will tend to inflate the value of $Var(U_t)$ above that given by Equation S2 as described below. But for this autocorrelation to have any impact on regression model estimation it needs to differ between days so that variance is inflated more on some days than on others.

Days of few potlifts tend to involve more rain, wind and cold air temperatures compared to days when more fishers fish and so differences in fisher skill may matter less resulting from increased interference in the process of fishing (i.e. less inter-fisher variability in catch rates relative to overall between-pot catch rates). Also, days with few pots tend to increase during the last 2 or 3 months of the fishing season and this implies reduced abundance (population depletion by fishing) making lobsters scarcer and more spatially diffuse perhaps further reducing spatial autocorrelation. Near the end of the season effective fishers drop out of the fishery (as their catch quota is caught), which likely reduces inter-fisher skill variability for remaining fishing days and the degree of clustering.

Mathematically the effect of clustering on variance can be expressed in formulae the form of which depend on the type of clustering assumed. For instance for a fixed number of pots assumed equal for all fishers, that is $P_{t,l} = P$, the following modification of Equation S2 applies

$$Var(U_t) \ \approx \ (S^2 / P_t)(1 + (P-1)\rho_t) \tag{S3}$$

where ρ_t is the within-fisher correlation coefficient (Cochran, 1977) expressing homogeneity among catches belonging to pots of the same fisher with $\rho_t \approx (S_f^2 - S^2)/((P-1)S^2)$ where S_f^2 is proportional to the between-fisher variance in catch totals. From Equation S3 it is clear that for days with reduced differences between fishers, and hence lower ρ_t, $\mathrm{Var}(U_t)$ is lower.

The effect on the variance of catch rates, from changes in both spatial autocorrelation and inter-fisher variability in the form of a positive relationship between ρ_t and P_t, is modelled by dividing S^2 by a modified form of P_t namely $\omega_t = (P_t)^{1/m}$ for $m \geq 1$. Increasing m means decreasing discrepancy in $\mathrm{Var}(U_t)$ between days of low and high potlift counts.

The above described effects of variance scaling of daily catch rates (U_t) also apply approximately for the variance (σ_t^2) of $\log(U_t)$ for day t. $\mathrm{Var}(U_t)$ in terms of σ_t^2 expressed to a first-order approximation in a Taylor series expansion provides $\sigma_t^2 \approx \mathrm{Var}(U_t)/(E(U_t))^2$, and since $\mathrm{Var}(U_t)$ is inversely proportional to potlifts hence so is σ_t^2. Note that later in the fishing season catch rates are naturally lower but so are daily potlift counts. Hence the weighting of $\mathrm{Var}(\log(U_t))$ via division by raw potlifts has to some extent a counteracting influence on the log-transformation of catch rates. However the power function modification of the potlifts acts concordantly with the log-transformation.

Log-transformed catch rate model likelihood

The log-transformed catch rates assume the parameter vector β consists of all the parameters in the model, *k* in number, $\{\beta_i\}_{i=0}^{k}$, along with matrix *X,* and vector y consisting of the *n* normally distributed response data, and this vector is estimated by finding the β_i that maximise the likelihood function

$$\frac{1}{\sqrt{(2\pi\sigma^2)^n |V|}} \exp(-(y - X\beta)^T V^{-1} (y - X\beta)/(2\sigma^2)), \qquad \text{S4}$$

where V is a diagonal matrix of all zero values off-diagonal and *n* non-zero constants along the main diagonal $\{1/\omega_t\}_{t=1}^{n}$. This means that in relation to β it amounts to minimising a weighted sum-of-squares, of weights equal to ω_t, via maximising the term inside the exponential in Equation S4.

Log-transformed daily catch rate data versus bottom temperature data pattern

A scatter plot of log-transformed daily catch rate data versus bottom temperature is shown in Figure S2.

Trends in log-transformed catch rate data and bottom temperature against day of fishing season

A plot of log-transformed catch rate and bottom temperature is shown against day of the 2007/08 fishing season for the South Australian Southern Zone in Figure S3.

Models used in the analysis

A complete list of models applied in the present study is presented in Table S1.

Standardised catch rates

It was of interest to calculate a so-called standardised catch rate series in order to obtain a monthly relative abundance time index and compare it to raw data catch rate. Catch rate standardisation consists of the removal of catchability effects from predicted catch rates, and assumes that remaining time effects represent changing lobster abundance.

However, the two estimated time-environment interaction terms, Mn:WaveH and Sn:T, are potentially influenced by longer term (over months and seasons) changes in catch rates, through either or both abundance or catchability. For instance, Sn:T and seasonal means of temperature data are positively correlated (r=0.88, p=0.004) implying that larger Sn:T might reflect an increase in seasonal abundance via increased growth (when affected positively by temperature).

But the regression model cannot causally distinguish between influences, and this is reflected in confounding between the time and time-environment interaction terms, making Mn:WaveH and Sn:T difficult to interpret physically (Maunder and Punt, 2004). In order to avoid these difficulties and obtain a standardised catch rate series involving more clearly the filtering out only of short-term environmental catchability factors, use is made of a model that has Sn:Mn as the only interaction term (Hinton and Maunder, 2004).

Figure S4 displays the season-month catch rate data series (monthly catch weight / monthly potlifts) together with the estimated median standardised catch rate (Sn+Mn+Sn:Mn) from the reduced model defined as:

$$\mu_t = \mathrm{Sn} + \mathrm{Mn} + \mathrm{Sn} : \mathrm{Mn} + \mathrm{WaveH} + \mathrm{WaveP} + \mathrm{T} + \mathrm{Moon} + \mathrm{MFAi} + \mathrm{WaveHLagAvg}\ .$$

The differences between the data and standardised catch rate series are relatively small compared to inter-month and inter-seasonal differences in either of the series. Note that, for this model, the estimated impact on mean catch rates of an increase in bottom temperature of 2.2°C (IQR) is a reduction of 10% (95% CI −12% to −8%), and the impact of an increase in wave height of 1.1 m (IQR) is a reduction of 7% (95% CI −8% to −5%).

Modelling of the Western Zone Victorian catch rates

In order to test the wider applicability of the methodology and results in this study, the South Australian Southern Zone analysis was repeated using data from a neighbouring lobster fishery, the Western Zone (WZ) of Victoria. The WZ Victorian rock lobster fishery extends from the South Australian border eastward to longitude 143.67º.

Victorian catch log data were screened and selected, providing daily aggregated catch rate (kg pot-lift^{-1}) covering the period from November 1994 to September 2010. These data span Victorian fishing seasons 1994 to 2009 where each fishing season runs from November (Mn=1) to September (Mn=11). The same environmental data series used in the SA analysis were used here for moon phase, wind, and sea surface height. Similarly so for wave data except a different point source was chosen (approx. Gps 39°S 142.5°E, depth 110 m, approx. 100 km south-east off Portland), which is centrally located within the WZ Victorian fishery region. The Victorian daily bottom temperature data (A. Levings, pers. comm.) were from two closely positioned bottom loggers (approx. 38.5ºS 141.5ºE, 80 m depth, approx. 30 km south off Portland), covering (with gaps) 1 February 2001 to 13 May 2007. Daily temperature values were averaged from midday to midday to obtain one daily data series. Spatial covariates used were average depth fished and average longitude fished on each day.

Additional days of catch rate data were removed from the "screened and selected" data set to avoid empty day identifier fields (7 days), 0 catch values (7 records), fishing in closed season (13 records), and fishing locations east of the Western Zone (5 records). Many more fishing days were removed due to environmental covariates being absent, notably bottom temperature, resulting in 1095 days remaining for analysis. Table S2 displays (over the same seasonal extent as the SA analysis) the temporal distribution of the remaining data in seasons 2000, 2001, 2004, 2005, and 2006. Monthly sampling imbalance across seasons is evident.

The Victorian model selection procedure started from the same full model as SA. The final model obtained after backward model selection was, with 55 estimated parameters,

$$\mu_t = \mathrm{Sn} + \mathrm{Mn} + \mathrm{Sn} : \mathrm{Mn} + \mathrm{WaveH} + \mathrm{WaveP} + \mathrm{T} + \mathrm{WaveHLagAvg} + \mathrm{Mn} : \mathrm{WaveH}\ .$$

WaveHLagAvg was found best fitted over lag periods 3 to 6 days, and a 3-day lag period was chosen for the same reason as for SA. The final Victorian model included no terms not also in the final SA model. But unlike for SA, the analysis did not find sufficient statistical support for moon phase, average longitude fished, or seasonal temperature difference. Model selection statistics are presented in Table S3. The signs of all estimated coefficients were the same as for SA. Temperature and same day wave height effects were negative (but strongest for June to August). Lagged wave height and wave period effects were positive. Wave height was the environmental covariate explaining the most variance in log-transformed catch rate. The proportion of total variance explained (adjR^2) by all the terms (including season and month) in the final Victorian model, 86.9%, was also similar to that for SA. The time-only terms (Sn+Mn+Sn:Mn) explained nearly the same amount, being 83.1% for Victoria's WZ and 84.3% for SA's SZ. However, the percentage variance explained by environmental covariates was 3.8%, less than the 7% found for SA.

The model selection process was repeated on the supplied non-screened-non-selected catch rate data set to examine the impact of screening and selecting of the catch and effort data. The final model obtained for this version of the analysis was

$$\mu_t = \mathrm{Sn} + \mathrm{Mn} + \mathrm{Sn} : \mathrm{Mn} + \mathrm{WaveH} + \mathrm{WaveP} + \mathrm{T} + \mathrm{MFAi} + \mathrm{Mn} : \mathrm{WaveH} + \mathrm{Sn{:}MFAi} + \mathrm{Mn{:}T} + \mathrm{WtauAS} + \mathrm{Mn{:}WtauAS},$$

which still excludes moon phase and seasonal temperature effects, but now excludes lagged wave height and includes a number of additional effects not in the screened-selected model nor in the SA model. Total variance explained using this analysis was 88.0% with the total environmental covariate component being 4.8%. The terms in common with the screened-selected final model had the same coefficient signs (negative for both temperature and same day wave height for all months). However, it may be presumed that all the new terms are spurious given that the non-screened-non-selected data set is considered less reliable.

The absence of the MFA index from the final Victorian model applied to the screened–selected daily-CPUE is a consequence of the variable selection procedure; i.e. after starting with all variables, elimination of the MFA index covariate was found to be appropriate according to the model term selection rules. MFA was not used as a correlate factor because the environmental data were available only at the level of zone, i.e. measured at single location in the zone. The use of the spatial MFA index reflects the hypothesis that catch rate varies with distance northwestward along the coast of the Southern Zone. Importantly, zero catch rates were not an issue because catch rates used are daily catch rates for the entire fleet across the zone and zeros catch rates did not occur.

Table S1. List of all model formulations used in the study.

Linear predictors	Data set	Variance weight	Autocorrelation	Description
Sn*Mn + WaveH + WaveP + T + Moon + SSH + Wtau + WtauAS + MFAi + Depth + bivariate time interactions + some lags	Full, 1258 days	Fixed, m = 3	None	Starting model, at start of backward selection.
Sn*Mn + WaveH + WaveP + T + Moon + MFAi + Mn : WaveH + Sn : T + WaveHLagAvg	Full, 1258 days	Fixed, m = 3	None	Final model, at end of backward selection.
Sn*Mn	Full, 1258 days	Fixed, m = 3	None	Time-only model, for comparison with Final model.
Sn*Mn + T	Catch rates and temperatures different per MFA. Days for MFAs 55, 56, 58: 702, 1286, 535.	Fixed, m = 3	None	Spatially-specific temperature logger submodels.
Final model.	Catch rates different per < 40 and >= 40 meters depth. Days for 1227 and 1206 respectively.	Fixed, m = 3	None	Depth-conditioned data submodels.
Final model - excluding MFAi.	Catch rates different per MFA. Days for MFAs 55, 56, 58: 1209, 1190, 1213.	Fixed, m = 3	None	MFA-conditioned data submodels.
Final model - excluding MFAi.	Catch rates only for MFA and depth < 40 meters, different per group of top 50% and bottom 50% fisher catch rates. Days for top and bottom: 1098, 1119.	Fixed, m = 3	None	MFA-depth-fisher-conditioned data submodels.
Final model.	Full, 1258 days	Fixed, separately for m values between 1 and 8.	None	Variance weight alteration - static effect on final model decision criteria.
Final model.	Full, 1258 days	Fixed, m = 3	Fixed, corAR1	Autocorrelation in the residuals - static effect on standard errors on parameters in the final model. Via gls().
Final model - excluding Sn:Mn.	Full, 1258 days	Estimated, via varPower	Estimated, corAR1	Estimating effects of residual autocorrelation and variance weight parameters on submodels. Via gls().
Final model - excluding MoonPhase + adding tide levels.	Full, 1258 days	Fixed, m = 3	None	Influence of tides through moon phase.
Final model + adding cloud cover levels.	Full, 1244 days	Fixed, m = 3	None	Influence of cloud cover on moon phase.
Final model: Gamma errors.	Full, 1258 days	Fixed, m = 3	None	Comparison between Gaussian and Gamma error distributions.

Table S2. Number of days per fishing season and month used in the Victorian modelling.

	Mn 1 (Nov)	Mn 2 (Dec)	Mn 3 (Jan)	Mn 4 (Feb)	Mn 5 (Mar)	Mn 6 (Apr)	Mn 7 (May)	Mn 8 (Jun)	Mn 9 (Jul)	Mn 10 (Aug)	Mn 11 (Sep)	Off-season (Oct)	All
Sn 1998	0	0	0	0	0	0	0	0	0	0	0	0	0
Sn 1999	0	0	0	0	0	0	0	0	0	0	0	0	0
Sn 2000	0	0	0	27	31	30	29	30	31	31	0	0	209
Sn 2001	8	29	31	27	31	28	29	21	29	29	0	0	262
Sn 2002	0	0	0	0	0	0	0	0	0	0	0	0	0
Sn 2003	0	0	0	0	0	0	0	0	0	0	0	0	0
Sn 2004	14	27	31	25	31	27	28	6	0	0	0	0	189
Sn 2005	13	29	31	28	29	27	27	28	25	31	0	0	268
Sn 2006	12	28	29	26	29	30	13	0	0	0	0	0	167
Sn 2007	0	0	0	0	0	0	0	0	0	0	0	0	0
Sn 2008	0	0	0	0	0	0	0	0	0	0	0	0	0
All	47	113	122	133	151	142	126	85	85	91	0	0	1095

Table S3. Impact of excluding given combinations of terms from the final Victorian model.

Term excluded	Δ-AICc	Reduction in adjR^2	Estimated parameters	Anova_Pr(>F)	Sign of coefficient
WaveP	-48.6	0.006	54	3.8E-12	+ve
T	-44.9	0.006	54	2.3E-11	-ve
WaveHLagAvg	-20.6	0.003	54	3.2E-06	+ve
Mn:WaveH	-82.4	0.012	46	5.2E-17	
WaveH + Mn:WaveH	-214.7	0.030	45	7.2E-43	-ve (notably Jun - Aug)
All covariate terms (time-only model)	-262.3	0.038	42	1.2E-51	
None (final model)	0	0	55	-	

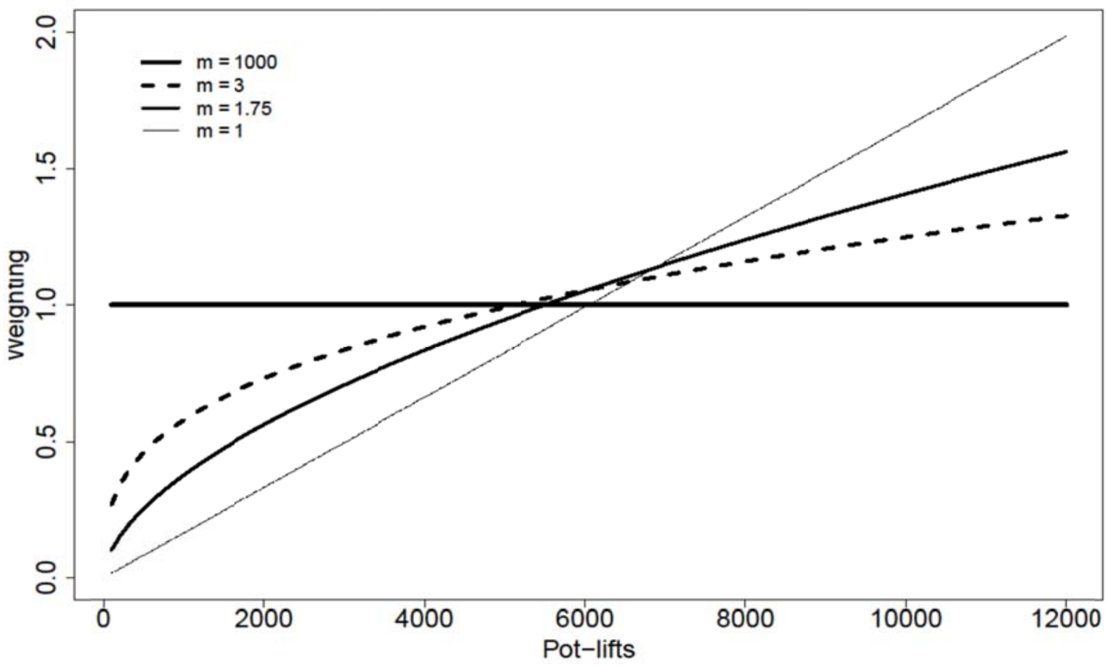

Figure S1. Regression weights as a power function of daily potlifts for different exponents (relative to means). The dashed line describes the curve implemented in the final regression model, the horizontal line involves no weighting, and the diagonal line involves weighting by raw potlifts.

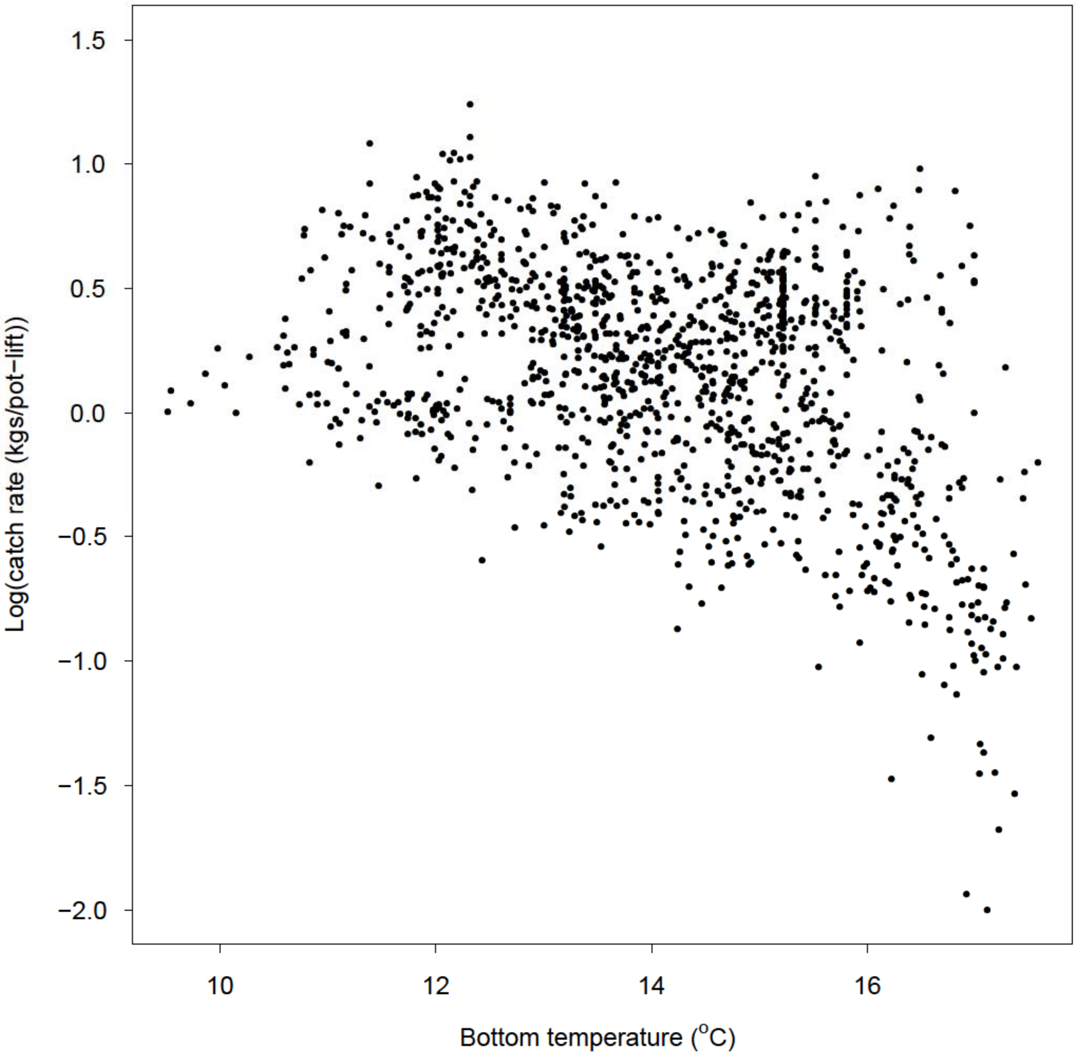

Figure S2. Scatter plot of log-transformed daily catch rate data for the Southern Zone fishery and bottom temperature data off Southend (60 m depth) used in the final model.

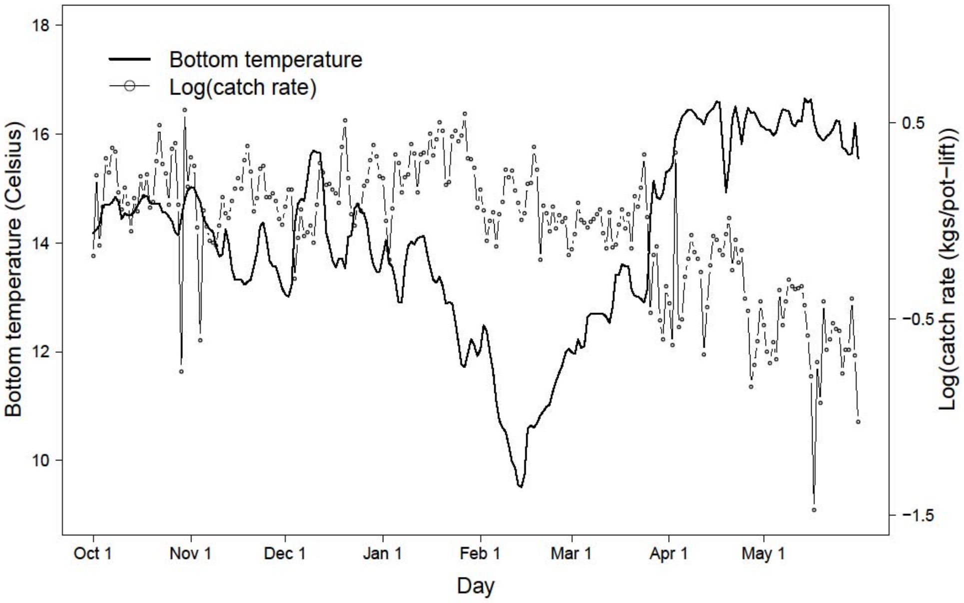

Figure S3. Log of daily catch rate and bottom (60 m depth) temperature data off Southend during the 2007/08 Southern Zone rock lobster fishing season.

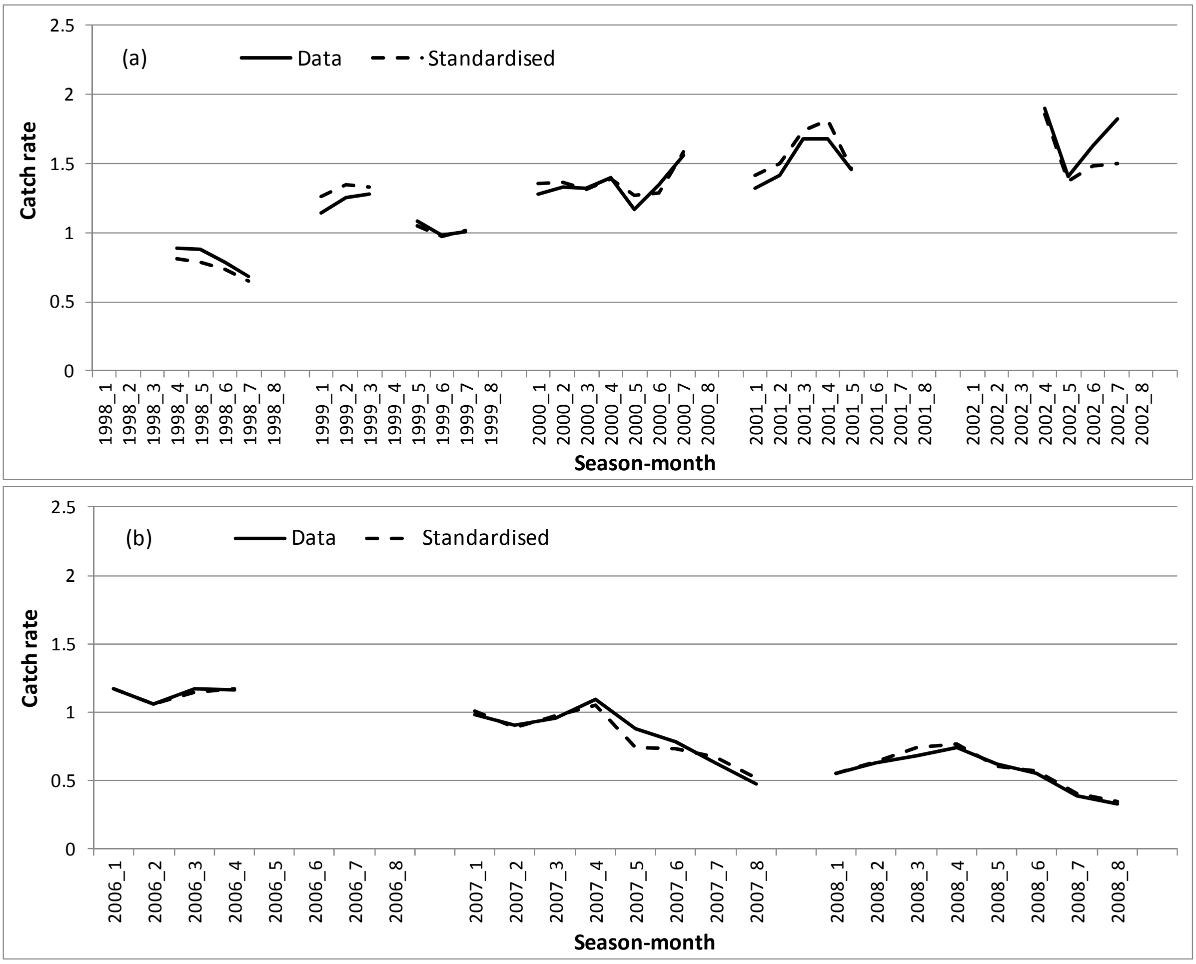

Figure S4 Monthly data and estimated median standardised catch rate series, presented separately for (a) period 1998−2002 and (b) 2006−2008. Values for each series were scaled by geometric means across months.

Catchability determination from seasonal depletion and recovery cycles of stocks of southern rock lobster (*Jasus edwardsii*) in the Victorian fishery (Australia)

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Abstract

Seasonal depletion and recovery cycles are evident for southern rock lobsters (SRLs) from logbook data standardised as monthly catch-per-unit-effort (CPUE) expressed as SRL number per potlift during each of 34 fishing-years and, for females and males separately, during each of seven fishing-years when data were collected at-sea by scientific observers on monthly sex-ratio of legal-sized (available) SRLs. Patterns of these cycles are consistent with the hypothesis that SRLs moult and grow to produce recruitment adding to the residual available-stock either prior to or shortly after the start of the fishing-year (November–September), before subsequent stock depletion through several months and then gradual recovery through the rest of the fishing-year. Depletion for females and males combined occurs during February–June, for females during November–May, and for males during January–June, consistent with the hypotheses that the moult-growth-recruitment process is protracted among females during June–October and among males during July–December. For females and males separately, where males lag two months behind females, a simple Leslie–DeLury stock-depletion model applied to five selected months in each of the seven fishing-years indicates that catchability is very similar between the sexes. Furthermore, catchability estimates over the entire 34-fishing-year period determined by depletion models from data for the four months February–May (sexes combined) provide inter-annual trends in a measure of changing fishing efficiency by the fleet, which can be used for adjusting standardised-CPUE used as an index of relative abundance. Understanding these seasonal cycles provides information on how best to group months for catchability estimation and to control protracted monthly-growth in a synthetic model that is length-based and used for stock assessment and setting the total allowable commercial catch for the fishery. That model integrates several exogenously determined biological and fishery parameters as it is fitted simultaneously to several sets of monitoring data. Results from the present study indicate that application of the stock-assessment model in Victoria can be improved in three ways. (1) Replace annual with bimonthly growth-transition matrices applied during each of six monthly time-steps during the stock-recovery months. (2) Alter estimation of catchability from each month separately to the months grouped November–March, April, May, and June–October. (3) Adjust standardised CPUE input data applied as indices of relative abundance by factors of annual fishing efficiency, whilst allowing for constant catchability inter-annually in the model.

Introduction

In the Victorian fishery for southern rock lobsters (*Jasus edwardsii*) (SRL), there is a statutory requirement for up-to-date stock-assessment to set annually a total allowable commercial catch (TACC) for each of the Western Zone (WZ) and Eastern Zone (EZ) (Fig. 1) (Anonymous 2009). According to a revised management plan (unpublished), the stock performance indicator of ‘available biomass’ (i.e. total mass of those SRLs in the population any time that can be caught legally) is to be 173% in the WZ and 219% in the EZ of the available biomass levels (target biological reference points) at the start of 2001–02 (reference fishing-year) by the start of 2020–21 (final-rebuild fishing-year). Each year the TACC required to allow for a stock recovery by 2020–21 is estimated using a purpose-built SRL-fishery stock-assessment-model designed for assessment of the SRL fisheries in Victoria (Hobday and Punt 2001; Hobday and Punt 2009; Hobday *et al.* 2005), South Australia (Linnane and Crosthwaite 2009), and Tasmania (Punt and Kennedy 1997). This integrated model is a size-structured population dynamics model in which, for each sex separately, growth is represented by a growth-transition matrix specifying the probability of a SRL growing from one size-class to each of a range of size-classes in a specified time-step. Up to and including 2011, the model was applied at the spatial level of zone in annual time-steps that assumed no spatial or temporal variation in the growth of SRL within a zone. Growth, and hence recruitment, was applied at the end of October, immediately prior to the beginning of each fishing-year (1 or 16 November to 14 or 30 September depending on legislation for closed seasons applied to both females and males) (Walker *et al.* 2011).

For the 2012 (Walker *et al.* 2012) and 2013 (Walker *et al.* 2013b) stock assessments, the latest version of the model was operated in monthly time-steps, rather than annual time-steps, from November to October, with August and September pooled to ensure sufficient monitoring data at each step. The model was operated with 5-mm size-classes (starting size 60 mm carapace length) with updated annual growth-transition matrices from a separate study (Walker *et al.* 2013c) (Appendix V), which were also applied at the end of October. The assessment model has several fixed parameters determined exogenously and is fitted to all available monitoring data sets. For each sex, in addition to the single growth-transition matrix, instantaneous natural mortality, and the relationships of total body mass to carapace length (CL) (sex specific), egg mass to CL (females only), proportion mature to CL (females only), and pot selectivity to CL (with and without escape-gaps fitted in the lobster pots) (sexes combined) are held constant across each zone for all fishing-years. Changing from annual to monthly time-steps for application of the assessment model created the need to consider the cycle of depletion of the available stock (legal-sized SRLs) for about the first half of the fishing year followed by protracted growth and recruitment during the second half and to consider how catchability might vary during the cycle. Catchability is estimated by the assessment model with facility to have separate estimates for selections of individual or groups of months where each selection applies equally to females and males and is constant over time. Hence, in the assessment model, to account for catchability changing over time caused by changing fishing-effort efficiency requires applying a time-series of assumed or exogenously determined annual adjustment-factors to the standardised-CPUE time-series adopted as indices of relative abundance.

Summary logbook catch and effort data indicate that CPUE is high during the early months (November–February) of the fishing-year, and subsequently reduces before rising for males until the end of the fishing-year, but not females which have the additional closed season from 1 June to the end of the fishing-year (i.e. open only for males). This pattern of seasonal depletion over several months of each fishing-year is explored by using simple Leslie–DeLury stock-depletion models (DeLury 1947; Leslie and Davis 1939). This is undertaken separately for females and males of carapace length (CL) greater than the legal minimum CL (105 mm CL for females and 110 mm CL for males) against the hypothesis that SRLs moult and grow to produce recruitment adding to the residual stock either prior to or soon after the start of the fishing-year. Understanding these patterns in seasonal stock-depletion is needed to determine how best to control estimation of the catchability parameter values and the timing of growth to provide recruitment to the exploited phase of the population in the assessment model.

Catchability is a concept that expresses the efficiency of a fishery by relating catch to abundance and is a measure of the quality of the fishing gear, fishing fleet and adopted harvest strategy developed from knowledge of fish behaviour (Arreguín-Sánchez 1996).

Catchability in a lobster fishery is affected by construction and use (e.g. bait and soak time) of the fishing gear (Arreguín-Sánchez 1996); by the capacity of the vessels to move between fishing sites, to locate fishing sites with navigational aids, to operate under varying conditions, and to carry and to deploy lobster pots effectively; by the fishing skill, experience and persistence of the fishers; and by economic incentive for the fishers to operate (e.g. price). Behavioural and other biological factors include presence of predator species (e.g. octopus) or other lobsters in a lobster pot deterring or attracting further entry (gear saturation) (Miller 1990), sex, size and condition related to growth (moult timing) and reproduction (timing of maturity, mating and egg laying) (Morgan 1974b). Habitat (Morgan 1974a), environmental factors such as salinity, temperature, and wave height (Morgan 1974b; Wright *et al.* 2006) (Appendix II) and astronomical cycles such as lunar cycles (Morgan 1974b; Wright *et al.* 2006) (Appendix II) are all known to affect catch rates and hence catchability.

Many of these factors contributing to variation in catchability are not important when considered at the spatial scale of zone or region of the fishery or the time frame of month or fishing-year adopted for the present study, and variation in catchability attributable to differences among vessels and fishers and locality (10 minutes of longitude specified for logbook reporting) and depth of fishing are accounted for (at least in part) though CPUE standardisation (Walker *et al.* 2013a) (Appendix I). Potentially much more significant over broad time-scales includes catchability increasing with declining stock abundance, as identified for clupeoid species through re-aggregation into schools easily located by fishers (Murphy 1977), but this is unlikely for SRLs as there is no evidence of re-aggregation after depletion for this species. More relevant to the present study is catchability can be affected by the amount of fishing effort; various studies show an inverse relationship between stock abundance and fishing effort (Arreguín-Sánchez 1996). In addition, other studies indicate catchability changes over time from progressive efficiency gains provided by improved technology (e.g. colour echo-sounders, satellite navigation, GPS and associated computer plotters). These studies indicate that estimates of changing catchability (proxy for changing fishing efficiency) provide a basis for adjustment of CPUE used as an index of relative abundance in stock assessment (Wright *et al.* 2006).

Potential for catchability to be affected by the level of fishing-effort or by incrementally improving technology is investigated as part of the present study using two alternative equations allowing catchability to vary with fishing-year within a Leslie–DeLury stock-depletion model. Patterns of inter-annual variation in annual estimates of catchability from intra-annual depletion during selected months were examined to provide a direct measure of efficiency change during the period from 1978−79 to 2011−12, which can be used for adjusting CPUE to provide a more reliable index of abundance (Wright *et al.* 2006). By applying adjustment factors for the effects of inter-annual change in fishing-effort efficiency to the standardised CPUE used as input data to the assessment model ensures that the assumption of constant catchability in the assessment model is valid.

Methods

In summary, intra-annual seasonal patterns in stock-depletion and the significance of the depletion to stock assessment were examined in three steps. Step 1 was to examine monthly plots of standardised-CPUE (SRL number per potlift) determined directly from logbooks for the sexes combined during each of 34 fishing-years in the WZ and the EZ and, in the WZ only, for females and males separately during each of 7 fishing-years when data were available on sex ratio in the catch collected at sea by scientific observers. Step 2, based on the patterns of depletion evident from Step1, was to fit a simple within-fishing-year depletion model to a selection of several months of the monthly standardised-CPUE data for the purpose of exploring inter-annual trends in estimates of the catchability parameter determined for each of 34 separate fishing-years, and for the purpose of testing whether catchability differed between females and males during the 7 fishing-years when the data can be divided into the two sexes. Step 3 was to evaluate the results from the present study for application in the assessment model.

Step 1 required screening, selecting and standardising commercial catch and effort logbook data to provide monthly standardised-CPUE expressed as SRL number per potlift. All logbook data were used for determining monthly total catch mass and number of SRLs. A system designed to screen out erroneous and incomplete data and to select CPUE data from vessel-fishers (concatenation of vessel and fisher) contributing data in >2 fishing-years and ≥200 records for hauls of >15 potlifts using the computer statistical package SAS (version 9.3) (SAS Institute, Cary, North Carolina, USA) provided screened−selected data for CPUE standardisation. A generalised linear model based on the Tweedie probability density function (Tweedie 1984) log-linked applied for CPUE standardisation included the main effects of fishing-year, fishing-month, longitudinal-range, depth-range, and vessel-fisher and second-order interactions (except vessel-fisher) for the 34-fishing-year period from 1978−79 to 2011−12 (Walker *et al.* 2013a) (Appendix I). Standardised CPUE expressed as kg per potlift was converted to number per potlift from monthly mean mass of SRLs determined from logbook data. For each of the seven fishing-years from 2005−06 to 2011−12, the monthly number of SRLs in the total catch and the monthly number of SRLs per potlift were split into numbers of females and males using summary data available on monthly sex-ratio in the catch from data collected at sea by scientific observers.

Step 2 used monthly catch numbers and monthly standardised CPUE data assembled for Step 1 and estimated catchability q applicable to the stock-depleting phase of the fishing-year and number of SRLs in the population 'available' for capture (i.e. SRLs larger than the legal minimum CL) N_{0t} at the beginning of or at some early instant during fishing-year t using a simple Leslie–DeLury stock-depletion model (DeLury 1947; Leslie and Davis 1939). This depletion model is suitable for a closed population of residual 'available' SRLs from past fishing-years and for those SRLs of size less than the legal minimum CL that moult and grow to reach legal size once a year to provide recruitment adding to the residual stock prior to the start of the stock-depleting phase of the fishing-year. A depletion model for monthly time-step m with M monthly time-steps during the depleting months of fishing-year t of T fishing-years can be expressed by the equation

$$CPUE_{t,m} = q_t N_{0t} - q_t \sum_{m=1}^{M} C_{tm}$$

where $CPUE_{tm}$ is catch per unit effort in fishing-month m of fishing-year t and $\sum_{m=1}^{M} C_{tm}$ is cumulative catch in fishing-month m of fishing-year t and t varies from 1 to T fishing-years. The equation allows for linear regression of $CPUE_{tm}$ against $\sum_{m=1}^{M} C_{tm}$ for estimation of parameters $q_t N_{0t}$ and q_t and calculation of N_{0t}. The slope of this linear relationship provides an estimate of q_t (proportion of available population taken by one unit of fishing effort) and extrapolation of the relationship down to the point where $CPUE_{tm}$ is zero provides an estimate of N_{0t} (Ricker 1975).

Two separate equations expressing inter-annual variation in catchability q_t in the depletion model were applied to investigate the change in catchability as a measure of change in the efficiency of the fleet over the 34-fishing-year period from 1978–79 to 2011–12. For the present study, these are referred to as the 'linear catchability-equation' and the 'effort-related catchability-equation'.

The 'linear catchability-equation' assumes that catchability varied linearly from the effects of continuous technological change, where the 34-fishing-year period is divided into two separate periods at the start of 2001–02 with adoption of fishery management with TACCs and individual transferrable quota units (ITQs). The period before TACC-ITQ adoption is from 1978–79 to 2000–01 and the period after TACC-ITQ adoption is from 2001–02 to 2011–12. In the 'linear catchability-equation', mean annual change in catchability for the period before TACC-ITQ adoption (i.e. $t = 1 - 23$) is represented by Δq_B and for the period after TACC-ITQ adoption (i.e. $t = 24 - 34$) is represented by Δq_A. This provides a trend in q_t relative to q in the last fishing-year of the period before TACC-ITQ adoption (i.e. t=23 designated by t=t_B). Varying catchability q_t with t (i.e. annually) in the depletion model required estimating the three parameters q, Δq_B and Δq_A in the equation given by

$$q_t = \mathrm{q} + \sum_{t=1}^{t_B} \Delta q_B(t_B - t) + \sum_{t=t_B+1}^{T} \Delta q_A(t - t_B)\,.$$

The 'effort-related catchability-equation' assumes that catchability q_t in fishing-year t varies depending on the level of standardised fishing-effort f_t (total catch/standardised CPUE) rescaled to a mean of 1 for the entire 34-fishing-year period and ignores the timing of TACC-ITQ adoption. This provides a trend in q_t relative to $\sqrt{f_t}$. Varying catchability q_t with t in the depletion model required estimating the two parameters q and Δq in the equation given by

$$q_t = q\, exp^{-\Delta q \sqrt{f_t}}\,.$$

Catchability q_t in any fishing-year t is related to f_t by the expression $exp^{-\Delta q \sqrt{f_t}}$. Preliminary tests by changing this expression to $exp^{-\Delta q f_t}$ (i.e. removing the square root function from the exponential term) had negligible effect in altering this trend.

If catchability is affected the level of standardised fishing effort, then it follows that catchability varies with month because of a general trend of decreasing effort as month progressed from February through March and April to May. Mean average monthly effort for the 34-fishing-year period for each of the four months expressed as a percentage of February were respectively were 100, 97, 76, 58% in the WZ and 100, 87, 59, 36% in the EZ. Hence, the 'effort-related catchability-equation' assumes that catchability $q_{t,m}$ in fishing-month m for each of the four months of fishing-year t varies depending on the level of standardised fishing-effort $f_{t,m}$ (total catch/standardised CPUE fishing month t, m) rescaled to a mean of 1 across the four fishing-months for the entire 34-fishing-year period. This provides a values of $q_{t,m}$ relative to $\sqrt{f_{t,m}}$. Varying catchability $q_{t,m}$ with m and t in the depletion model required estimating the two parameters q and Δq in the equation given by

$$q_{t,m} = q\, exp^{-\Delta q \sqrt{f_{t,m}}}$$

in the model

$$CPUE_{t,m} = q_t N_{0t} - \sum_{m=1}^{M} q_{t,m} C_{t,m}\,.$$

Annual catchability q_t was then calculated from the estimates of the two parameters q and Δq in the equation given by

$$q_t = q\, exp^{-\Delta q \sqrt{f_t}}\,,$$

which enabled calculation of N_{0t}.

The data were fitted to the depletion model by minimising the difference between the observed and expected values of monthly standardised CPUE for the 34-year period (sexes combined) or 7-year period (sexes separate) when estimating the various parameters catchability and initial population size at the beginning of the stock-depleting phase of each fishing-year. The log-likelihood function (LnL) was maximised by applying "Solver" in EXCEL to minimise differences between the observed and expected values. The maximum log-likelihood function is

$$LnL = \sum_{t=1,m=1}^{T,M} [-\left(\frac{(Exp_{tm} - Obs_{tm})^2}{2Var}\right) - Ln\left(\sqrt{2\pi Var}\right)]$$

where

$$Var = \frac{\sum_{t=1,m=1}^{T,M}(Exp_{tm} - Obs_{tm})^2}{n - p}\,,$$

and where n is the number of observations (i.e. number of fishing-years x number of selected fishing-months of depletion for each fishing-year), p is the number of parameters estimated, Var is variance, Exp_{tm} and Obs_{tm}denote the expected value predicted by the depletion model and the observed value, respectively, during fishing-month m for M fishing months of fishing-year t for T fishing-years.

For each of the 'linear catchability-equation' and the 'effort-related catchability-equation' separately, a factor for annual adjustment of standardised CPUE for change in fleet efficiency was determined by rescaling q_t to a geometric mean of 1 for the entire 34-fishing-year period. Although rescaled q_t is an annual quantity, it is appropriate to adjust annual or monthly (or any other within-year period) standardised CPUE by dividing standardised CPUE in fishing-year t by the 'annual-efficiency adjustment-factor' for fishing-year t.

Step 3 was to examine and to interpret the implications of the results from the present study on the operation of the assessment model, which is fitted simultaneously to monthly catch (mass and number), standardised CPUE, and SRL-CL-frequency composition of the catch (above and below legal minimum CL), and accounts for SRL population biology processes and fishery dynamics, and estimates q. In that model, q can be estimated for each month or groups of two or more months. Potential behavioural and physiological responses to seasonal conditions and to the reproductive cycle create uncertainty on how best to control catchability and recruitment seasonally, where protracted seasonal recruitment is controlled in the model by the timing of growth. Correct timing of growth increment in the assessment model reduces confounding between q and recruitment during the parameter estimation processes.

Results

Step 1 data summaries of monthly and annual catch numbers during fishing-years from 1978–79 to 2011–12 assembled from non-screened–non-selected data provided on mandatory commercial logbook returns indicate a trend in the WZ of a general decline during the 1980s, increase to a peak during the 1990s, and another decline during the 2000s, and a trend in the EZ a of general decline throughout this period. Both zones exhibit a halt to the overall declines at the end of the time-series (Table 1). Monthly SRL number per potlift from 1978–79 to 2011–12 produced from screened–selected logbook data, which were standardised-CPUE expressed as kg per potlift and then converted to SRL number per potlift provided different trends. In the WZ, catch rates decline to the mid-1990s with some recovery until the early 2000s before continuation of the decline, whereas in the EZ a general decline occurred through to the mid-1990s, followed by a subsequent rise. Both zones exhibit a marked recovery in the last three fishing years of the time-series (Table 2; Fig. 2). Trends in monthly catch numbers and SRL number per potlift weighted by sex ratio in the catch from the on-board observer program and annual fixed-site survey in the WZ (Table 3) for each of the seven fishing-years from 2005–06 to 2011–12 indicate that 31–43% of the overall number of SRLs caught were female (Table 4). The comparatively robust estimates of sex ratio presented in Table 3 were based on recording sex of 22,719 female and 29,519 male SRLs over the 7-fishing-year period. There was insufficient sex-composition sampling to prepare similar summaries in the EZ.

Seasonal trends indicated by the Step 1 data summaries show a consistency over the entire period from 1978–79 to 2011–12 of the highest standardised-CPUE (SRL number per potlift) for females and males combined occurring at the beginning of each fishing-year and remain fairly constant during the four months November–February, then decline to a minimum by June, before a subsequent rise for the rest of the fishing-year (Table 2, Fig. 2). However, the summaries by sex for each of the seven fishing-years from 2005–06 to 2011–12 in the WZ show a marked difference in the seasonal trends between females and males (Table 4, Fig. 3). Females exhibit a continual decline during November–May until the female seasonal-closure starting 1 June, whereas males initially rise during November–January, decline during January–June, and rise during June–January (Fig. 4). These trends are consistent with the hypothesis of full recruitment of females by November and full recruitment of males two months later by January followed by very similar patterns of depletion over the following five months (Fig. 5). For males, following the five-month decline, there is a general rise during June–January. An increasing trend for females is not evident, because of the closed season for females during June–mid-November, other than the sex ratio progressively favouring females during June–November. Hence, these patterns are consistent with the hypothesis of annual cycles of peak recruitment followed by six months of progressive depletion and then six months of protracted recruitment, before peaking again and repeating the cycle, where the females precede the males by two months. The lowest standardised-CPUE values observed for females during April and May might be explained by reduced catchability associated with entering the moult phase of the cycle. For males, on the other hand, increasing standardised-CPUE during July–September when fishing effort is low, which approaches the levels of standardised-CPUE occurring during November–December when fishing effort is high. In addition to protracted recruitment, this might be explained, at least in part, by large differences in gear competition between these periods (Fig. 4).

The clear linear depletions for females during November–May and for males during January–June provided a basis for using the Leslie–DeLury stock-depletion model (Step 2) for estimating N_{t0} and q_t for these parts of the fishing-year for the two sexes separately and combined by regression of $CPUE_{tm}$ against cumulative catch $\sum_{m=1}^{M} C_{tm}$, where $M = 5$, and $T = 7$. For this analysis q_t is assumed constant for all 7 fishing-years for each sex separately, and the two sexes combined, and the depletion model was parameterised to N_{t0} and q (Fig. 6). For females, because $CPUE_{tm}$ declines markedly during April and May, which is a likely indicator of falling catchability, N_{t0} and q were estimated for the five-month-period November–March of each of the 7 fishing-years. For males, because the closed season for females results in targeting males and potentially biasing catchability, June was excluded from the analysis and N_{t0} and q were estimated for the five-month-period

January–May of each of the 7 fishing-years. The estimates of catchability from the depletion model were very similar for females (q=1.322 x 10^{-6} year^{-1}) and males (q=1.442 x 10^{-6} year^{-1}) (Table 5).

Female and male recruitment being out of phase by about two months has a smoothing effect on standardised CPUE through November–February when the sexes are combined. Understanding this phenomenon, together with the result of no significant difference in catchability between females and males, indicates that it is appropriate to use only the 4-month-period February–May (i.e. $M = 4$) for estimating combined-sex catchability q_t for each fishing-year of the 34-fishing-year period from 1978–79 to 2011–12. The 4-month depletion for each of the 34 fishing-years (i.e. $T = 34$) provide for a wide range of depletions in both the WZ and EZ (Fig. 7a and b). A sensitivity test extending the 4-month-period to the 5-month-period January–May (i.e. $M = 5$) shows that the trend in q_t produced by the depletion model with the 'effort-related catchability-equation' is sensitive to the adopted length of the stock-depleting phase (Figs 7c and d). Hence, results produced from the 5-month period are considered less valid than those produced from the 4-month period because of the lack of difference between the January and February standardised CPUE values (Figs 2 and 3a). Of the total annual catches during the 34-fishing-year period, 42.5% in the WZ and 31.2% in the EZ were caught during the 4-month February–May stock-depleting phase, whereas 46.9% in the WZ and 49.4% in the EZ were caught during the 3-month November–January pre-depletion phase, and 10.2% in the WZ and 19.4% in the EZ were caught during the 4-month June–September post-depletion phase (Table 1).

Trends in q_t of rising catchability during the period after TACC-ITQ adoption are common to the WZ and EZ, but are very different between the WZ and EZ during the period before TACC-ITQ adoption (Figs 7c, d), Declining catchability during the period before TACC-ITQ adoption in the WZ produced by the Leslie–DeLury stock-depletion model used with the 'linear catchability-equation' is inconsistent with the hypothesis of continuous technological change where improved technology is expected to increase catchability. The linear decline is very similar to the pattern in catchability produced by the depletion model used with the 'effort-related catchability-equation', which is indicative of catchability in the WZ being more influenced by fishing effort than by technological change. It appears that if any efficiency gains by the fleet had occurred from improved technology, they have been masked by the effects of gear competition. In the EZ, the difference in the trends between the use of the 'linear catchability-equation' and the 'effort-related catchability-equation' in the depletion model are much more marked than for the WZ. The high variation in the magnitude of $\sqrt{f_t}$ over the 34-fishing-year period has a much higher effect in the EZ than in the WZ.

The significance of this difference becomes apparent when catchability (rescaled to a geometric mean of 1 for the 34-fishing-year period) is applied as an adjustment factor for efficiency change to the time-series of standardised CPUE (Figs 7e, f). The adjusted standardised-CPUE trends determined from the adjustment factors from use of the two catchability-equations in the depletion model are more similar for the WZ than the EZ, and the effects of the adjustments are greater in the EZ than in the WZ. In the WZ, the time-series of adjusted standardised CPUE starts and ends below the unadjusted standardised-CPUE, but is above during the 1990s and early 2000s. In the EZ, the time-series of adjusted standardised CPUE is mostly above the unadjusted standardised-CPUE until the end of the 1990s, when it falls below for the rest of the time-series, indicating greater long-term than does the unadjusted standardised-CPUE

Estimates of annual catchability (geometric mean) from the depletion model using the 'effort-related catchability-equation' are about five times higher for the EZ (15.11 x 10^{-6} year^{-1}) than for the WZ (2.94 x 10^{-6} year^{-1}) (Table 5). Population size of legal-sized SRLs at the start of February tends to be fairly stable until a decline in the last decade of the time-series in the WZ, but has gradually declined through the entire time-series in the EZ (Figs 7g and h).

Discussion

Several important conclusions are drawn from the present study that contribute to improving application of the SRL-fishery stock-assessment model in Victoria (Walker *et al.* 2013b), which has been adapted for harvest strategy evaluation (Punt *et al.* 2013). (1) Improved understanding of the moult-growth-recruitment process enables replacing annual with bimonthly growth-transition matrices applied during each of six monthly time-steps in the assessment model. (2) The appropriate grouping of months for catchability estimation by the assessment model is November–March, April, May, and June–September. (3) Two options are available to account for efficiency changes by the fleet. One option is to alter the data input from standardised CPUE as an index of SRL relative abundance to standardised CPUE adjusted by an 'annual-efficiency adjustment-factor' whilst maintaining the assessment model's assumption of constant catchability inter-annually. The alternative option is to replace constant $q_{m'}$ in the assessment model with the expression

$$q_{m'}\, exp^{-\Delta q\sqrt{f}_{m'}}$$

where catchability $q_{m'}$ and standardised fishing effort $f_{m'}$ accounting for gear competition apply to the time interval of month or group of months m'.

For the formal stock-assessments of 2012 and 2013, as for earlier assessments, growth, and hence recruitment, were applied in a single time-step during October using an annual growth-transition matrix for each sex separately. However, on the basis of the results from the present study, the assessment model was successfully tested with two basic changes, where the tests applied to each region separately rather than at the level of management zone as applied for formal stock-assessment. The first change involved applying bimonthly growth-transition matrices rather than annual growth-transition matrices. This allowed for protracted growth and protracted recruitment by applying bimonthly growth-transition matrices during each of six time-steps separately for females (April–October) and for males (June–December) when most growth is during the closed season for females (June–October). The second change involved changing from estimating q for each month to estimating q for the months grouped November–March, April, May, and June–September. For one region, the model fitted best to the data when April was grouped with November–March for the estimation of q.

Unbiased estimates of q and N by the Leslie–DeLury stock-depletion model depend on key assumptions of the model: the population is closed (i.e., no immigration or emigration) and there is no recruitment and no natural mortality. For the present study, the assumption of a closed population is reasonable because although it is known that the SRLs move among separate inhabited reefs, the fishing fleet operates over of all these reefs. The assumption of no recruitment is considered reasonable because the depletion model was applied to each sex separately for five months and to the two sexes combined for four months of the fishing-year when growth and hence recruitment do not appear to occur. The assumption of no natural mortality is most likely violated during the five months, but is considered sufficiently small not to markedly bias N and q estimates; an instantaneous natural mortality rate equivalent to an annual natural mortality rate of 10% is adopted for the assessment model. It is feasible to expand the model to include natural mortality (Chapman 1974; Tillman and Breiwick 1977), but is unnecessary for the purpose of the present study given the effect of natural mortality is expected to be only ~4% over a 4–5 month period.

Various controlled depletion-experiments have used dive and potting survey with tag release-recapture techniques to estimate catchability of lobsters taken in lobster pots. Whilst these experiments provide insights into catchability, they have been disappointing in providing robust estimates of catchability that can be applied as an exogenously determined parameter in an integrated stock-assessment model. Nevertheless, these experiments have been valuable in having detected strong behavioural interactions among SRLs such as negative association between small and large SRLs, where the effect was stronger during winter than summer; the differences in catchability with season, sex and size (Ziegler *et al.* 2002b); and the low impact of capture on the probability of recapture (Ziegler *et al.* 2002a).

Several problems arise with such depletion experiments relating mainly to spatial scale because they are conducted at scale small compared with the scale of an entire fishery and most likely produce catchability estimates unrepresentative of the fishery. (1) The experiments may be undertaken in locations of aggregations of particular components of the population affected by sex, size or maturity (Ziegler *et al.* 2002b). (2) Even when undertaken in areas where the fishery is excluded (Ziegler *et al.* 2002a), it is difficult to control for immigration to and emigration from the study site (Morgan 1974b). (3) Catchability varies markedly with among separate areas of differing habitat and ambient environmental conditions (Morgan 1974a). (4) Marking of lobsters may (Morgan 1974b) or may not (Ziegler *et al.* 2002a) affect the probability of recapture. Adaptations of depletion models for overcome problems posed by significant progressive recruitment through the season or by progressive change in q through the season include models referred to as change-in-ratio (Kelker 1940; Paulik and Robson 1969) and index-removal (Petrides 1949) applied *J. edwardsii* (Frusher *et al.* 2007; Frusher *et al.* 1997; Ihde *et al.* 2008; Ziegler *et al.* 2004) are unlikely to solve the problem of scale. Underwater surveys show that abundance and size composition in the population of *Panulirus cygnus* in Western Australia varies markedly with habitat type (Bellchambers *et al.* 2010) .

Working with data at the scale of the entire fishery overcomes the problem of scale and parameter estimates are expected to apply to the entire fishery, or as for the present study spatial level of management zone. Notwithstanding working with data at a wide scale, any departure from the assumptions of the Leslie–DeLury stock-depletion model will inevitably lead to biases in parameter estimation.

A study similar to the present study identified several sources of potential biases in estimation of catchability when working with wide-scale data from a fishery (Wright *et al.* 2006). That study of *Panuliris cygnus* harvested in Western Australia, expressing CPUE as body mass of females and males combined, identified the possibility of biases in catchability estimates caused by several factors affecting CPUE. These include the environmental factors of swell and bottom water temperature, the astronomical factor of moon phase, and biological factors such as the timing of moulting. However, a separate study of *J. edwardsii* (Feenstra 2013) (Appendix II) testing for the effects of swell, water temperature and moon phase shows that swell and moon phase do affect CPUE, but only over periods of higher temporal resolution of the data (day) than that applied in the present study (month). For the purpose of the present study, this indicates that the effects of swell and moon phase can be ignored, and temperature had only minor effect in the range 12–18 °C, with slight decreases in CPUE with increasing temperature of bottom of water in this range; above 18 °C the effect appears to be stronger as SRLs become progressively more inactive and stop feeding. Comparison of observed CPUE with expected CPUE adjusted for these tested environmental factors indicate that temperature of bottom water had no effect on CPUE and hence catchability of SRLs during the February–May stock-depleting phase of each of the fishing-years 2006–07 and 2007–08 (Feenstra 2013).

Bottom temperature appears to be is fairly constant through this period at depths of 20–30 m, but rises rapidly during this period in deeper water. West of the WZ, daily average bottom temperature obtained from the bottom loggers located on South Australia's coast off Southend, Port MacDonnell and Robe at depths of 50–55 m indicate that the Bonney Upwelling can cause bottom temperatures to fall 2–3 °C over a period of 5–10 days during December–March,. Overlying this cold water is a 20–30 m deep surface-mixed layer 2–3 °C warmer than that at the bottom. During April–June, south-easterly upwelling winds are replaced by westerly winds, and bottom temperatures rise by 4–5 °C, as the warm surface layer water is mixed to the bottom. During winter, the westerly winds, in conjunction with cooling, lead to down welling and a vertically well-mixed water column persisting until November–December, when winds again drive upwelling of cold water onto the shelf (Lewis 1981; Middleton *et al.* 2012). In the WZ, similar bottom, near-bottom and mid-water loggers at several sites off Western Victoria at depths of ~80 m reveal a similar widespread pattern of stratified waters through summer with rapid mixing of surface and bottom water giving rise to rapidly rising bottom water temperature during March in 2001 and 2006 from ~12 to ~16 °C (Levings and Gill 2010). This information indicates that bottom temperature is unlikely to have appreciably affect catchability. Whilst bottom temperatures would have inevitably gone outside the 12–18 °C range from time to time in specific areas of the waters off Victoria, the occurrence is unlikely to have marked effects on the results and conclusions of the present study.

The most difficult results from the present study to explain are the large differences in the mean annual catchability estimates between the WZ and EZ. For example, the February–May depletion-period determined from the Leslie–DeLury stock-depletion model with the 'effort-related catchability-equation' provided estimates of mean catchability for the 34-year period of 2.940 x 10^{-6} year^{-1} in the WZ and 15.114 x 10^{-6} year^{-1} in the EZ (Table 5), which is a factor of 5.14 difference. Contributing factors are likely to include larger SRLs in the EZ catch than in the WZ catch, more isolated lightly-fished reefs in the EZ than the WZ, lower densities and the common absence of under-sized SRLs on the main fishing grounds reducing gear saturation in the EZ more than the WZ. Food may be less available in the EZ than the WZ, but there are no data to support this conjecture. Further similar analyses at finer spatial resolution might improve these insights.

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Table 1. Monthly catch numbers during fishing years from 1978–79 to 2011–12

Data: non-screened and non-selected (see Walker 2013a).

Fishing year	Catch (number) for each month										
	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug–Sep	Total
Western Zone											
1978–79	64678	92733	94402	66547	70751	34549	12951	5653	6515	36171	484950
1979–80	73575	62992	78984	71451	53892	33819	12075	5662	9616	41595	443661
1980–81	91275	103349	106090	94489	61668	32845	11911	3744	7465	35633	548469
1981–82	80606	90249	99606	73132	65833	31059	9360	5568	8590	35093	499096
1982–83	73053	89766	69386	73841	53689	35624	13882	2700	8560	34530	455031
1983–84	60090	85971	81181	71615	45321	22733	13723	2876	5722	24512	413744
1984–85	52792	59756	81889	71481	53202	29553	12601	3506	4933	24248	393960
1985–86	66197	58576	57777	49388	46947	18476	9998	3087	5199	30237	345882
1986–87	56426	60152	58512	52973	50126	32540	8917	4518	7577	21339	353080
1987–88	25559	71856	73451	57150	55436	28905	12137	3999	6114	14243	348849
1988–89	22335	60798	56186	50766	50507	36048	13524	5569	10073	16690	322496
1989–90	29674	64910	72911	54116	60973	28742	11967	4859	9298	17181	354631
1990–91	21985	55034	63640	53639	51064	31530	20789	6344	16459	16305	336789
1991–92	33055	69995	78279	72633	69591	46528	29353	9662	12186	17987	439269
1992–93	26685	66188	93464	57461	67201	49250	25452	7867	17012	22591	433171
1993–94	42145	75414	67448	79618	83273	38667	20275	12494	15845	21284	456464
1994–95	34226	87951	91193	68963	53383	32005	29395	11543	13496	21960	444115
1995–96	34590	73872	86476	77732	67502	30987	28791	8631	14056	19326	441963
1996–97	30074	80091	73741	70105	51589	36998	22743	10413	15658	22453	413865
1997–98	38463	95737	100910	65065	63251	41221	26633	12164	16040	32959	492443
1998–99	45558	94894	96584	83099	81874	62475	32452	11602	20507	38610	567655
1999–00	52889	91115	93682	99918	78188	60256	30385	11275	26494	48287	592489
2000–01	63042	99995	122087	101717	68565	44611	36537	9848	23835	27672	597910
2001–02	41633	87013	103986	77680	61302	54858	32671	4180	12392	34507	510223
2002–03	48861	90599	101161	76395	49690	44965	38370	5975	12333	26214	494563
2003–04	46929	85737	83892	87395	69970	50880	32132	6520	13338	38219	515012
2004–05	44047	79920	83208	62429	54511	44772	27711	9647	9573	35271	451087
2005–06	39286	65144	92533	75294	51952	18828	12844	4195	10583	34774	405433
2006–07	33966	69546	66556	71507	52520	39847	16478	0	0	41121	391541
2007–08	41716	62768	68229	53623	49359	28395	15586	0	0	18318	337994
2008–09	22706	52712	57896	44249	34641	19138	13158	3604	5062	14495	267661
2009–10	24457	47539	49184	41431	34886	21720	18848	7479	10985	20042	276571
2010–11	26220	45416	62481	38595	36300	27481	11934	4457	16782	37647	307313
2011–12	27444	58142	47324	44341	28862	15557	6605	2916	16071	31799	279061
Eastern Zone											
1978–79	22546	19019	23011	12759	11139	6744	2849	600	2902	21232	122801
1979–80	15698	18317	17827	18391	9265	6233	2702	276	3524	16203	108436
1980–81	22943	20316	22757	17454	9901	5635	2900	433	3194	17220	122753
1981–82	17390	22905	21476	19515	12148	5341	1769	700	3162	15758	120164
1982–83	23424	23238	18906	19081	12731	6456	2711	1334	4650	19190	131721
1983–84	18192	22468	22304	21245	12452	7454	3176	661	3501	16698	128151
1984–85	19302	18644	17066	13015	10859	5352	1464	359	1284	8852	96197
1985–86	18237	16631	14229	9319	6152	3279	1795	433	1424	9171	80670
1986–87	11537	12532	10241	9241	6846	2910	757	501	2276	9320	66161
1987–88	7738	14176	14116	8649	7558	2670	952	543	1926	3821	62149
1988–89	6409	12795	12529	7750	6040	3494	772	393	3602	6310	60094
1989–90	9726	16606	15955	12261	10721	5494	1588	499	3536	8153	84539
1990–91	7670	13952	13529	10548	7084	3170	1687	549	5479	8065	71733
1991–92	7221	11654	9729	10678	8064	3853	1705	823	3406	6439	63572
1992–93	5270	11268	13240	8032	7624	4916	2036	762	4599	5591	63338
1993–94	9062	13422	12272	10233	8175	2804	1242	1022	3507	5963	67702
1994–95	5074	12489	11132	8452	5563	4213	2163	803	3488	4824	58202
1995–96	3795	7729	9026	7952	6386	2687	1370	1209	3473	4094	47721
1996–97	2869	8314	7632	7627	5386	2976	2062	1734	3839	5355	47794
1997–98	6847	10529	9298	6402	5249	2833	1797	1098	3972	6010	54035
1998–99	3957	9695	9912	8307	5226	4108	1998	1191	4739	8904	58037
1999–00	6346	11848	12266	12525	6910	4081	1185	1440	4329	10196	71126
2000–01	9927	14068	10752	7667	4245	3024	2182	1414	6208	7495	66982
2001–02	4877	9659	10281	5544	4690	2971	978	330	3336	7024	49690
2002–03	4895	8961	7756	6205	3735	4255	1662	328	3160	6935	47892
2003–04	4956	10859	7679	6097	4659	2024	1820	525	2543	9664	50826
2004–05	5898	8162	9907	4739	4630	2872	1340	767	2016	8178	48509
2005–06	4131	9321	9002	6330	4192	763	850	676	2352	8267	45884
2006–07	4103	8900	7491	7593	5194	2787	1528	605	2364	7057	47622
2007–08	4833	8786	5769	4167	4034	1961	1082	338	2833	4947	38750
2008–09	2354	5857	6313	2970	4100	2217	1144	577	2435	3746	31713
2009–10	3192	6786	6737	4964	3541	1971	1537	1055	5741	14207	49731
2010–11	5873	10598	11097	5983	3389	3076	2272	882	5121	14197	62488
2011–12	6139	12355	10331	3986	2303	2546	2317	769	5262	8750	54758

Data source: Fisheries Victoria CandE Database (11 January 2013)

Table 2. Monthly Tweedie standardised CPUE (number per potlift) from 1978–79 to 2011–12

Data: screened, selected and CPUE standardised as kg per potlift (see Walker et al 2013a), and converted to number per potlift.

Fishing year	Mean standardised CPUE (no. per potlift) for each month									
	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug–Sep
Western Zone										
1978–79	0.983	1.080	1.003	0.987	0.891	0.685	0.613	0.576	0.435	0.535
1979–80	1.032	1.010	0.989	0.984	0.890	0.723	0.602	0.612	0.543	0.604
1980–81	1.145	1.098	1.073	1.094	0.808	0.746	0.531	0.369	0.525	0.537
1981–82	0.981	1.038	1.057	0.965	0.891	0.680	0.563	0.508	0.453	0.532
1982–83	1.114	1.132	1.013	1.028	0.848	0.705	0.498	0.422	0.580	0.476
1983–84	0.865	1.010	1.005	0.921	0.748	0.611	0.527	0.308	0.470	0.487
1984–85	0.804	0.841	0.852	0.878	0.776	0.622	0.470	0.406	0.356	0.409
1985–86	0.795	0.762	0.775	0.745	0.696	0.467	0.383	0.280	0.277	0.395
1986–87	0.737	0.722	0.684	0.704	0.697	0.563	0.407	0.399	0.424	0.417
1987–88	0.667	0.752	0.781	0.768	0.728	0.586	0.363	0.285	0.326	0.408
1988–89	0.541	0.678	0.684	0.634	0.676	0.626	0.389	0.333	0.386	0.434
1989–90	0.662	0.731	0.769	0.726	0.659	0.507	0.354	0.266	0.339	0.354
1990–91	0.596	0.643	0.675	0.681	0.618	0.464	0.378	0.276	0.338	0.341
1991–92	0.716	0.788	0.863	0.843	0.764	0.629	0.471	0.348	0.313	0.375
1992–93	0.680	0.726	0.799	0.713	0.679	0.563	0.457	0.290	0.325	0.343
1993–94	0.781	0.783	0.697	0.799	0.717	0.500	0.404	0.289	0.289	0.308
1994–95	0.630	0.780	0.766	0.653	0.564	0.458	0.362	0.255	0.250	0.292
1995–96	0.621	0.731	0.780	0.775	0.647	0.428	0.338	0.231	0.249	0.251
1996–97	0.597	0.636	0.654	0.632	0.503	0.391	0.297	0.238	0.251	0.297
1997–98	0.605	0.756	0.764	0.646	0.543	0.468	0.348	0.257	0.253	0.359
1998–99	0.753	0.821	0.749	0.718	0.686	0.567	0.388	0.277	0.324	0.395
1999–00	0.807	0.789	0.782	0.776	0.609	0.519	0.385	0.263	0.334	0.396
2000–01	0.809	0.765	0.803	0.750	0.596	0.440	0.365	0.237	0.315	0.334
2001–02	0.778	0.755	0.845	0.877	0.775	0.603	0.425	0.280	0.302	0.376
2002–03	0.855	0.887	0.858	0.808	0.755	0.667	0.475	0.267	0.325	0.383
2003–04	0.689	0.832	0.793	0.885	0.763	0.622	0.468	0.320	0.317	0.362
2004–05	0.816	0.812	0.753	0.692	0.621	0.507	0.373	0.248	0.249	0.322
2005–06	0.697	0.618	0.702	0.615	0.498	0.369	0.245	0.176	0.287	0.299
2006–07	0.575	0.606	0.581	0.661	0.539	0.422	0.291	0.242	0.266	0.323
2007–08	0.662	0.555	0.572	0.545	0.487	0.341	0.242	0.239	0.263	0.212
2008–09	0.480	0.571	0.523	0.489	0.403	0.281	0.209	0.183	0.228	0.224
2009–10	0.527	0.497	0.499	0.490	0.418	0.331	0.274	0.208	0.239	0.267
2010–11	0.599	0.513	0.628	0.566	0.502	0.411	0.306	0.259	0.388	0.347
2011–12	0.642	0.638	0.618	0.595	0.508	0.450	0.336	0.258	0.347	0.377
Eastern Zone										
1978–79	0.597	0.684	0.752	0.657	0.534	0.435	0.386	0.221	0.478	0.605
1979–80	0.697	0.701	0.712	0.727	0.595	0.480	0.354	0.103	0.539	0.598
1980–81	0.725	0.735	0.781	0.709	0.513	0.493	0.356	0.201	0.432	0.623
1981–82	0.687	0.666	0.670	0.676	0.518	0.392	0.259	0.167	0.305	0.454
1982–83	0.717	0.674	0.722	0.744	0.583	0.405	0.343	0.262	0.425	0.526
1983–84	0.623	0.651	0.750	0.758	0.548	0.488	0.346	0.267	0.334	0.445
1984–85	0.500	0.492	0.497	0.512	0.416	0.344	0.251	0.168	0.159	0.303
1985–86	0.425	0.444	0.415	0.384	0.331	0.248	0.246	0.158	0.243	0.290
1986–87	0.420	0.414	0.399	0.410	0.390	0.317	0.228	0.184	0.287	0.324
1987–88	0.370	0.372	0.445	0.346	0.391	0.252	0.210	0.295	0.206	0.264
1988–89	0.364	0.408	0.419	0.366	0.304	0.224	0.155	0.204	0.285	0.314
1989–90	0.474	0.392	0.449	0.413	0.364	0.269	0.209	0.172	0.254	0.385
1990–91	0.370	0.396	0.423	0.444	0.367	0.278	0.258	0.197	0.398	0.446
1991–92	0.431	0.345	0.396	0.473	0.383	0.318	0.247	0.192	0.189	0.276
1992–93	0.367	0.355	0.321	0.290	0.265	0.214	0.204	0.149	0.164	0.169
1993–94	0.317	0.298	0.272	0.257	0.232	0.147	0.120	0.089	0.122	0.178
1994–95	0.204	0.236	0.228	0.205	0.173	0.159	0.126	0.096	0.138	0.163
1995–96	0.248	0.243	0.237	0.248	0.200	0.147	0.123	0.134	0.127	0.133
1996–97	0.171	0.201	0.188	0.179	0.148	0.142	0.149	0.103	0.138	0.178
1997–98	0.228	0.202	0.226	0.218	0.182	0.152	0.123	0.105	0.141	0.203
1998–99	0.239	0.233	0.253	0.265	0.210	0.202	0.142	0.126	0.184	0.259
1999–00	0.257	0.285	0.323	0.331	0.237	0.171	0.147	0.138	0.158	0.281
2000–01	0.368	0.335	0.274	0.246	0.206	0.182	0.176	0.149	0.212	0.234
2001–02	0.359	0.330	0.396	0.394	0.285	0.244	0.141	0.129	0.183	0.244
2002–03	0.340	0.318	0.341	0.368	0.282	0.305	0.211	0.133	0.196	0.351
2003–04	0.469	0.437	0.370	0.392	0.311	0.229	0.194	0.163	0.216	0.311
2004–05	0.492	0.463	0.400	0.316	0.314	0.284	0.151	0.159	0.190	0.264
2005–06	0.442	0.387	0.428	0.337	0.283	0.202	0.193	0.147	0.209	0.298
2006–07	0.391	0.412	0.449	0.428	0.294	0.262	0.208	0.130	0.169	0.259
2007–08	0.410	0.374	0.344	0.291	0.275	0.259	0.147	0.119	0.201	0.251
2008–09	0.387	0.346	0.319	0.277	0.278	0.243	0.168	0.129	0.212	0.203
2009–10	0.348	0.317	0.339	0.322	0.225	0.179	0.162	0.155	0.271	0.495
2010–11	0.508	0.443	0.509	0.447	0.327	0.299	0.184	0.145	0.324	0.422
2011–12	0.566	0.565	0.444	0.362	0.323	0.382	0.382	0.191	0.364	0.483

Data source: Fisheries Victoria CandE Database (11 January 2013)

Table 3. Proportions of legal sized female and male SRLs observed at sea from 2005–06 to 2011–12 in the Western Zone

SRL, southern rock lobster; nd, no data; fishing year, 16 November–31 May for females and 16 November–14 September for males; proportions based on recording sex of 29,519 male and 22,719 female SRLs.

Sex	Fishing year	Proportions of male and female SRLs observed each month									
		Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug–Sep
Female	2005–06	0.636	0.601	0.438	0.495	0.460	0.260	0.283	0.208	nd	0.547
	2006–07	0.689	0.562	0.484	0.458	0.432	0.357	0.300	nd	nd	0.414
	2007–08	0.560	0.498	0.423	0.409	0.419	0.302	0.134	nd	nd	0.407
	2008–09	0.554	0.574	0.390	0.416	0.375	0.387	0.344	nd	nd	0.490
	2009–10	0.534	0.428	0.441	0.405	0.477	0.403	0.229	0.113	0.551	0.487
	2010–11	0.454	0.486	0.372	0.351	0.388	0.320	0.175	0.154	0.364	0.336
	2011–12	0.477	0.410	0.381	0.362	0.352	0.339	0.248	nd	nd	0.517
	Mean	0.558	0.508	0.418	0.414	0.415	0.338	0.245	0.158	0.457	0.457
Male	2005–06	0.364	0.399	0.562	0.505	0.540	0.740	0.717	0.792	nd	0.453
	2006–07	0.311	0.438	0.516	0.542	0.568	0.643	0.700	nd	nd	0.586
	2007–08	0.440	0.502	0.577	0.591	0.581	0.698	0.866	nd	nd	0.593
	2008–09	0.446	0.426	0.610	0.584	0.625	0.613	0.656	nd	nd	0.510
	2009–10	0.466	0.572	0.559	0.595	0.523	0.597	0.771	0.887	0.449	0.513
	2010–11	0.546	0.514	0.628	0.649	0.612	0.680	0.825	0.846	0.636	0.664
	2011–12	0.523	0.590	0.619	0.638	0.648	0.661	0.752	nd	nd	0.483
	Mean	0.442	0.492	0.582	0.586	0.585	0.662	0.755	0.842	0.543	0.543

Data source: Fisheries Victoria onboard observer program and annual fishery-independent fixed-site survey (11 January 2013)

Table 4. Monthly catch number and standardised CPUE (number per potlift) for each sex from 2005–06 to 2011–12 in the Western Zone

cs, closed season; nd, no data; CPUE, catch per unit effort data screened, selected and Tweedie standardised (see Table 2 and Walker *et al* 2013a); data for months November–May are based on summary data from mandatory commercial logbooks for catch number (Table 1) and standardised CPUE expressed as kg per potlift, converted to number per potlift (Table 2), weighted by sex ratio in the catch from onboard observer program and fixed-site survey (Table 3), and, because retention of females is prohibited, data for months June–September are based directly on summary data from mandatory commercial logbooks for catch number (Table 1) and standardised CPUE expressed as kg per potlift converted to number per potlift (Table 2).

Fishing year	Catch number or standardised CPUE (catch number per potlift) for each month										
	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug–Sep	Total
Female catch											
2005–06	24992	39165	40550	37244	23910	4902	3629	0	0	0	174392
2006–07	23400	39109	32194	32739	22709	14225	4936	0	0	0	169313
2007–08	23367	31228	28846	21907	20704	8565	2083	0	0	0	136701
2008–09	12572	30252	22568	18410	12975	7401	4527	0	0	0	108705
2009–10	13052	20352	21669	16793	16625	8745	4314	0	0	0	101548
2010–11	11901	22059	23227	13551	14094	8794	2092	0	0	0	95717
2011–12	13100	23849	18021	16041	10151	5278	1640	0	0	0	88080
Male catch											
2005–06	14294	25979	51983	38050	28042	13926	9215	4195	10583	34774	231041
2006–07	10566	30437	34362	38768	29811	25622	11542	0	0	41121	222228
2007–08	18349	31540	39383	31716	28655	19830	13503	0	0	18318	201293
2008–09	10134	22460	35328	25839	21666	11737	8631	3604	5062	14495	158956
2009–10	11405	27187	27515	24638	18261	12975	14534	7479	10985	20042	175022
2010–11	14319	23357	39254	25044	22206	18687	9842	4457	16782	37647	211596
2011–12	14344	34293	29303	28300	18711	10279	4965	2916	16071	31799	190981
Female CPUE											
2005–06	0.444	0.371	0.308	0.304	0.229	0.096	0.069	cs	cs	cs	
2006–07	0.396	0.341	0.281	0.302	0.233	0.151	0.087	cs	cs	cs	
2007–08	0.371	0.276	0.242	0.223	0.204	0.103	0.032	cs	cs	cs	
2008–09	0.266	0.328	0.204	0.203	0.151	0.109	0.072	cs	cs	cs	
2009–10	0.281	0.213	0.220	0.199	0.199	0.133	0.063	cs	cs	cs	
2010–11	0.272	0.249	0.234	0.199	0.195	0.131	0.054	cs	cs	cs	
2011–12	0.307	0.262	0.235	0.215	0.179	0.153	0.083	cs	cs	cs	
Male CPUE											
2005–06	0.254	0.246	0.394	0.311	0.269	0.273	0.176	0.176	0.287	0.299	
2006–07	0.179	0.265	0.300	0.358	0.306	0.271	0.204	cs	cs	0.323	
2007–08	0.291	0.279	0.330	0.322	0.283	0.238	0.210	cs	cs	0.212	
2008–09	0.214	0.243	0.319	0.285	0.252	0.172	0.137	0.183	0.228	0.224	
2009–10	0.246	0.284	0.279	0.291	0.219	0.198	0.211	0.208	0.239	0.267	
2010–11	0.327	0.264	0.395	0.367	0.307	0.279	0.253	0.259	0.388	0.347	
2011–12	0.336	0.376	0.383	0.380	0.330	0.297	0.252	0.258	0.347	0.377	

Data source: Fisheries Victoria CandE Database (11 January 2013), and onboard observer program and annual fishery-independent fixed-site survey

Table 5. Summary of parameter estimates from Leslie-DeLury intra-annual depletion for the period from 1978–79 to 2011–12

na, not applicable.

Sex	Period of fishing-years	Zone	Catchability equation	Depletion months	Catchability parameters				Geometric-mean annual-catchability	Ln-likelihood (maximised)
					$q \times (10^{-6})$	Δq	Δq_B	Δq_A	$\bar{q}_t \times (10^{-6})$	
Female	2005–06 to 2011–12	Western	na[A]	November–March	1.322	na	na	na	na	84.197
Male			na[A]	January–June	1.442	na	na	na	na	74.041
Added			na[A]		1.501	na	na	na	na	156.317
Combined	1978–79 to 2011–12	Western	Linear	February–May	2.526	na	-0.0172	0.0369	3.015	195.017
			Effort related	February–May	6.656	-0.822	na	na	2.940	192.882
			Effort related	January–May	3.391	-0.568	na	na	1.926	197.973
Combined	1978–79 to 2011–12	Eastern	Linear	February–May	12.111	na	0.0064	0.0185	11.915	236.004
			Effort related	February–May	57.862	-1.354	na	na	15.114	257.312
			Effort related	January–May	68.559	-2.020	na	na	9.247	275.494

A, point estimate.

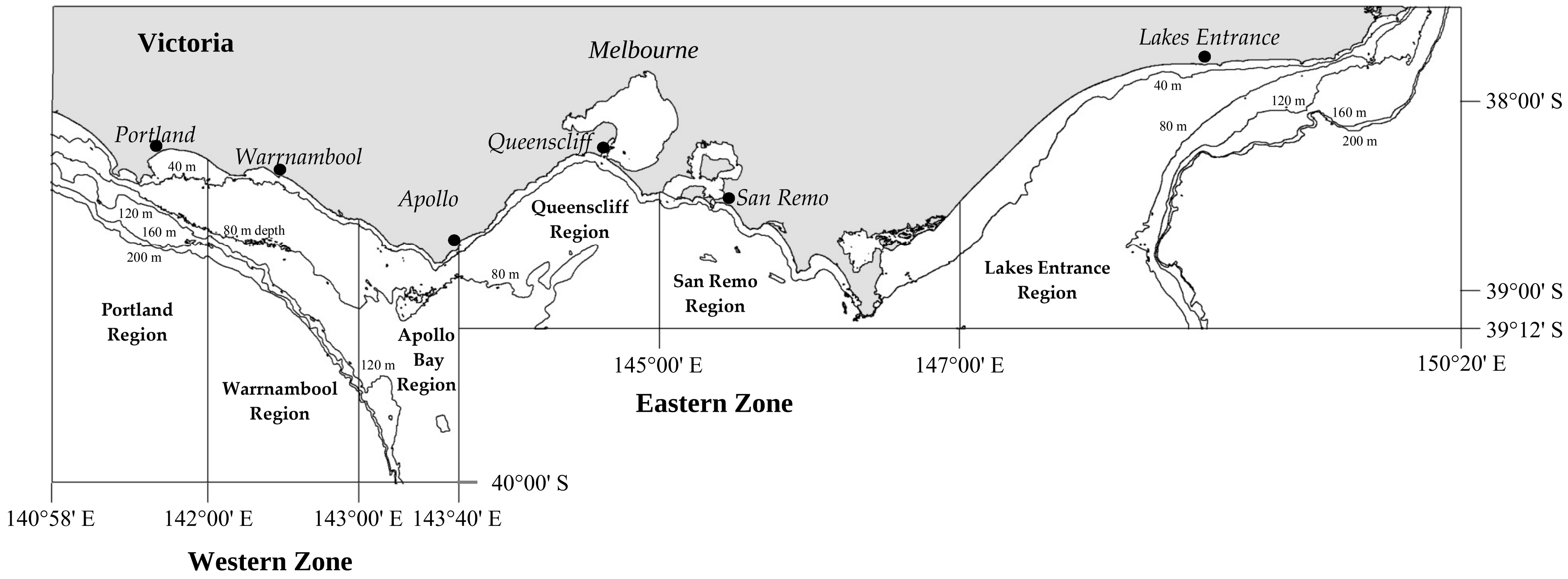


Figure 1. Western Zone and Eastern Zone in Victoria showing six regions

Western Zone is divided at longitudes 142°00' E and 143°00' E into Portland Region, Warrnambool Region, and Apollo Bay Region, and Eastern Zone is divided at longitudes 145°00' E and 147°00' E into Queenscliff Region, San Remo Region and Lakes Entrance Region where each region is named after its

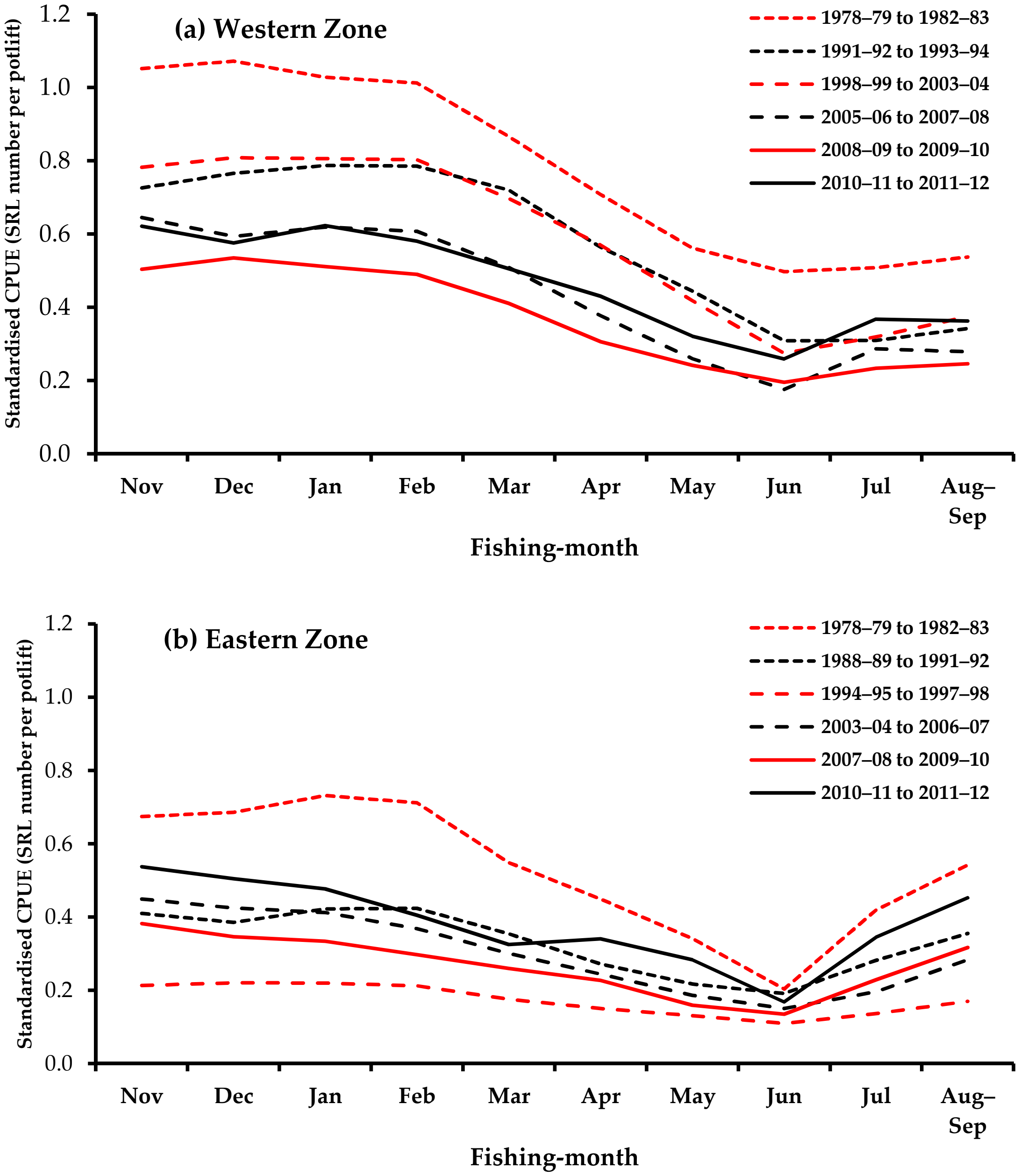


Figure 2. Trends in monthly standardised-CPUE for groups of fishing-years averaged

Trends are of monthly standardised CPUE from mandatory commercial logbook returns expressed as kg per potlift, converted to SRL number per potlift (Table 2), and then averaged for each month for a range

Data source: Fisheries Victoria CandE Database (11 January 2013)
and Fisheries Victoria onboard observer and fixed-site survey data

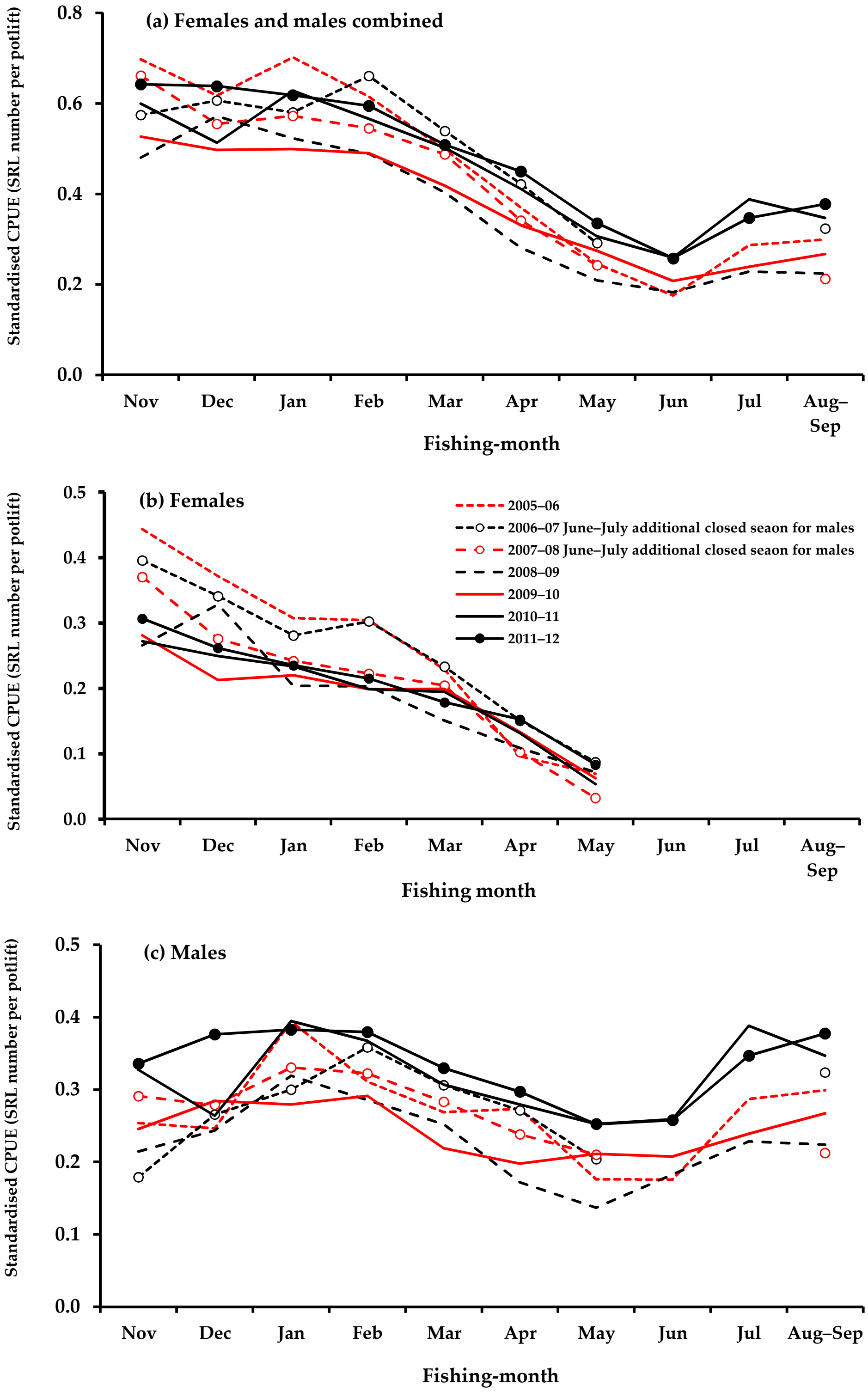


Figure 3. Intra-annual depletion of sexes combined (a), females (b), and males (c) in WZ

WZ, Western Zone; SRL, southern rock lobster; trends are of monthly standardised-CPUE from mandatory commercial logbook returns expressed as kg per potlift, converted to SRL number per potlift (Table 2), and weighted by sex ratio in the catch from onboard observer program and fixed-site survey (Table 3) for each of the seven fishing years from 2005–06 to 2011–12.

Data source: Fisheries Victoria CandE Database (11 January 2013)
and Fisheries Victoria onboard observer and fixed-site survey data

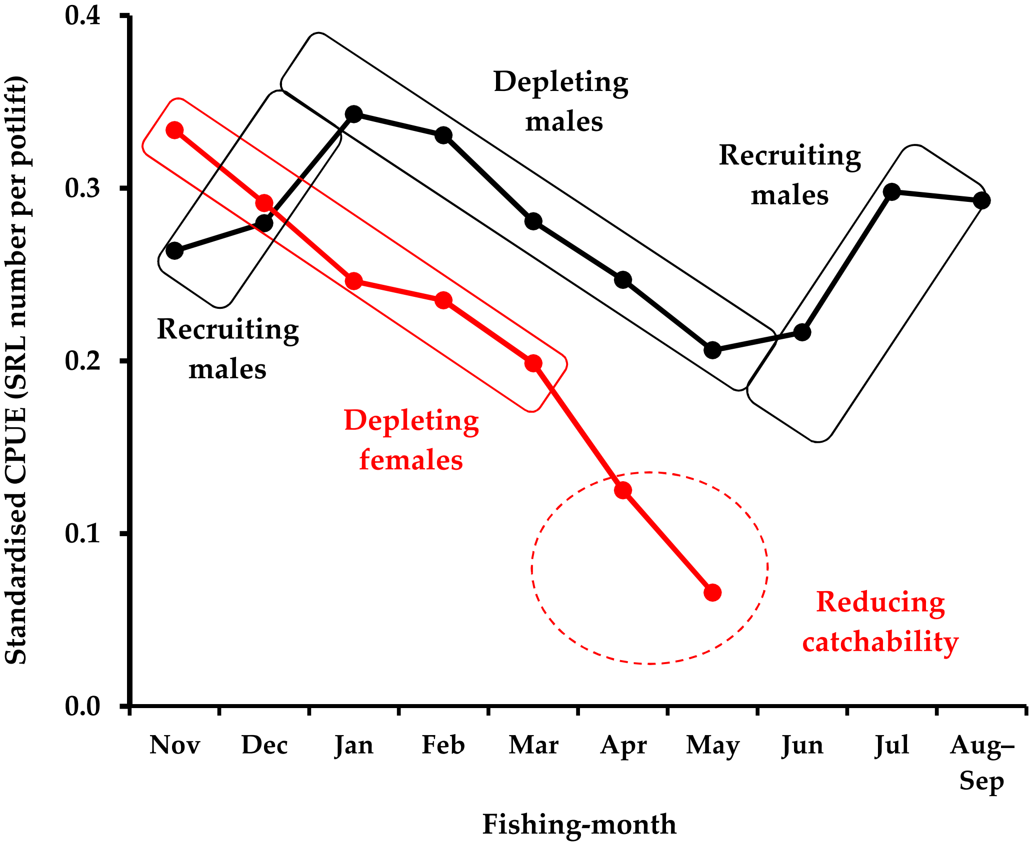


Figure 4. Average intra-annual depletion of female and male SRLs in the WZ

WZ, Western Zone; SRL, southern rock lobster; trends are of monthly standardised CPUE from mandatory commercial logbook returns expressed as kg per potlift, converted to SRL number per potlift (Table 2), weighted by sex ratio in the catch from onboard observer program and fixed-site survey (Table 3), and then averaged for seven fishing years from 2005–06 to 2011–12.

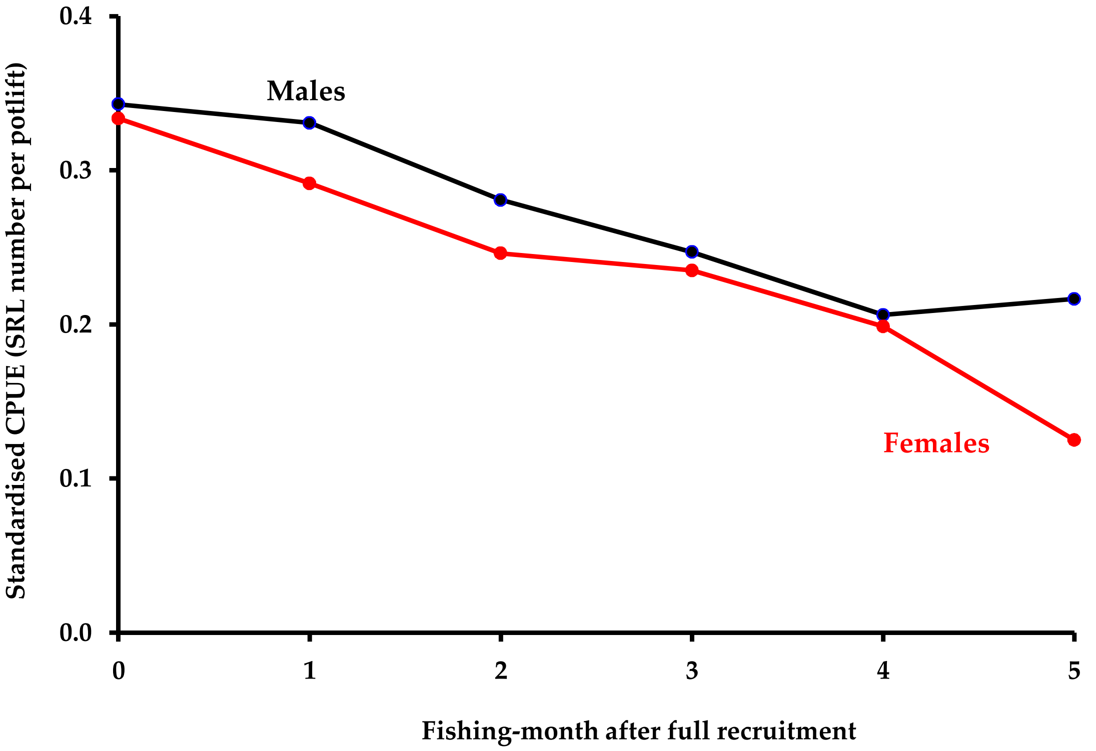
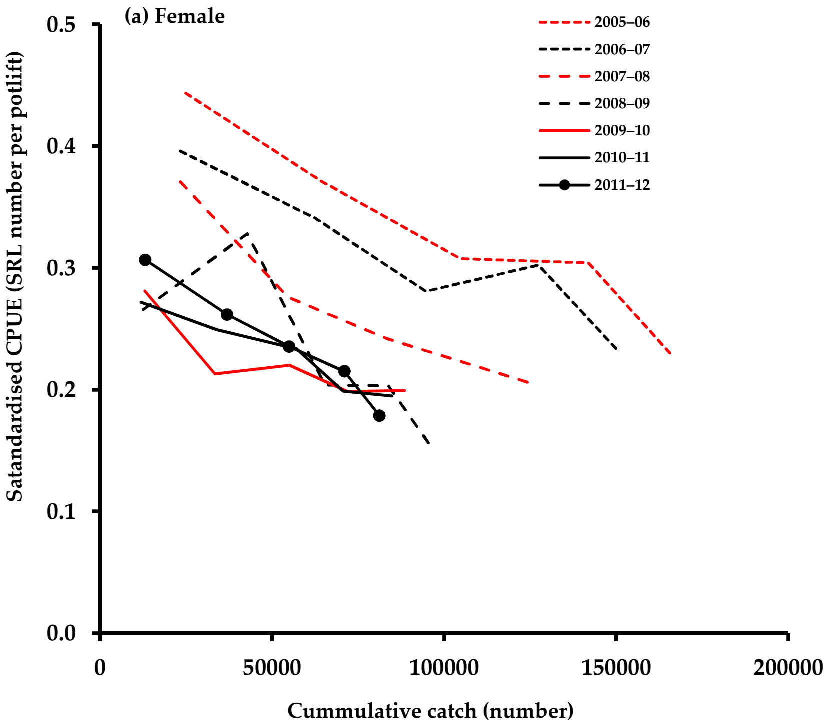


Figure 5. Depletion following full recruitment of females (November) and males (January)

Trends are of monthly standardised CPUE from mandatory commercial logbook returns expressed as kg per potlift, converted to SRL number per potlift (Table 2), weighted by sex ratio in the catch from onboard observer program and annual fixed-site survey (Table 3), and then averaged for seven fishing-years from 2005–06 to 2010–11; WZ, Western Zone; SRL, southern rock lobster.



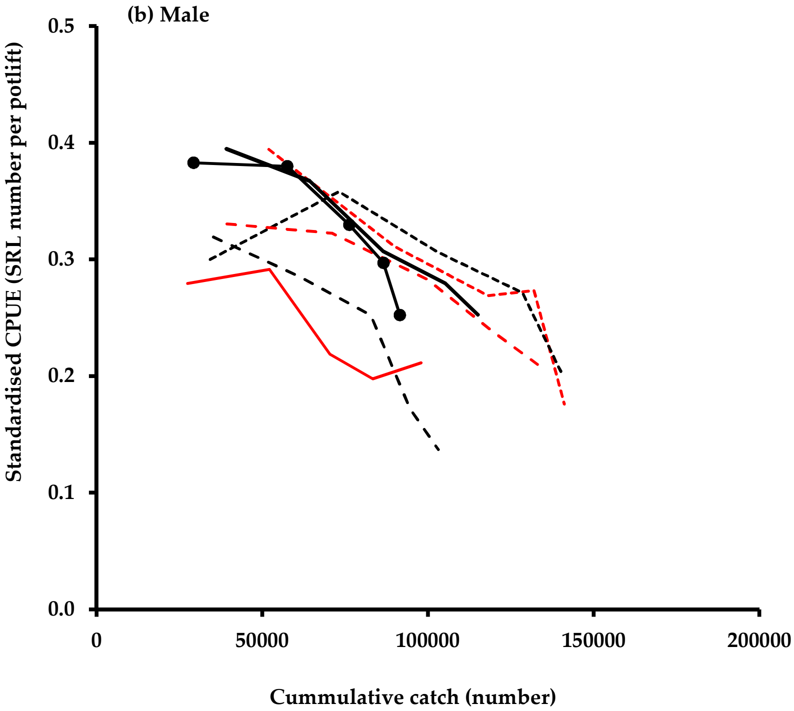


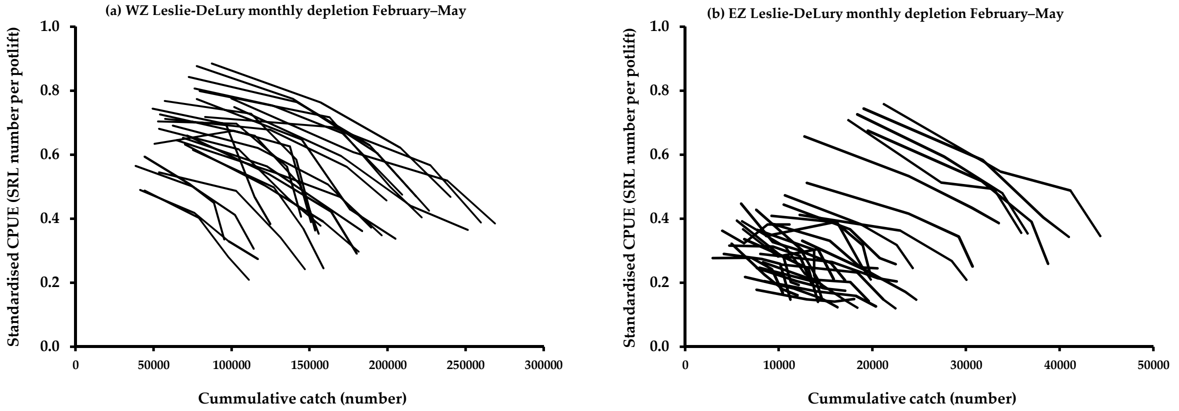
Figure 6. Leslie–DeLury monthly depletion of female (a) and male (b) SRLs in WZ

WZ, Western Zone; SRL, southern rock lobster, trends are of monthly standardised CPUE determined from mandatory commercial logbook returns expressed as kg per potlift, converted to SRL number per potlift (Table 2), and weighted by sex ratio in the catch from onboard observer program and fixed-site survey (Table 3) for each of seven fishing years from 2005–06 to 2011–12.

Data source: Fisheries Victoria CandE Database (11 January 2013)
and Fisheries Victoria onboard observer and fixed-site survey data

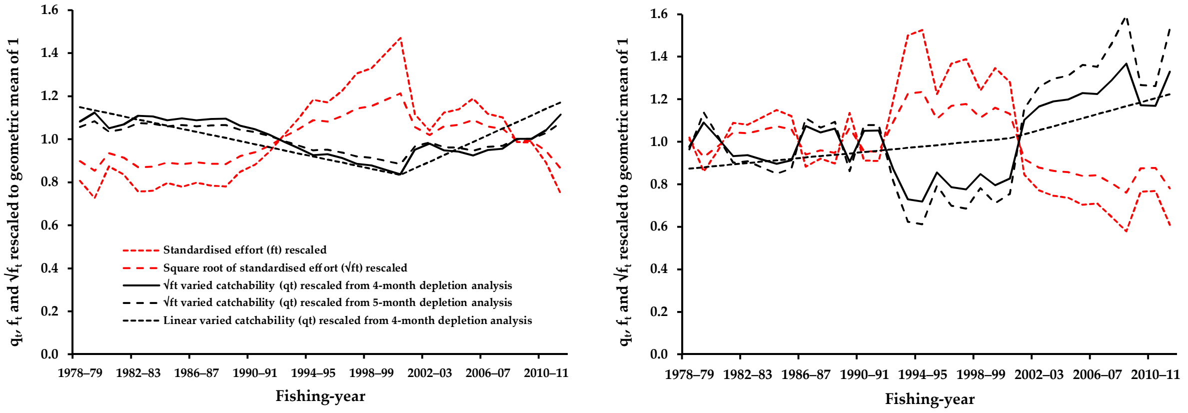
(a) WZ Leslie-DeLury monthly depletion February–May

(b) EZ Leslie-DeLury monthly depletion February–May



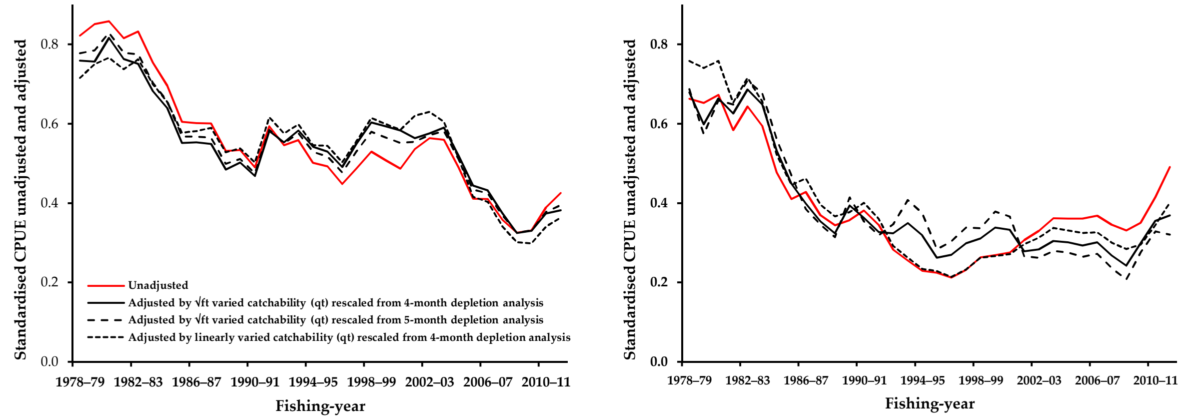
(c) WZ rescaled catchability (q_t) and rescaled standardised effort expressed as f_t and $\sqrt{f_t}$

(c) EZ rescaled catchability (q_t) and rescaled standardised effort expressed as f_t and $\sqrt{f_t}$



(e) WZ standardised CPUE unadjusted and adjusted by rescaled catchability (qt)

(f) EZ standardised CPUE unadjusted and adjusted by rescaled catchability (qt)



(g) WZ number of legal-sized SRLs in population at start of February

(h) EZ number of legal-sized SRLs in population at start of February

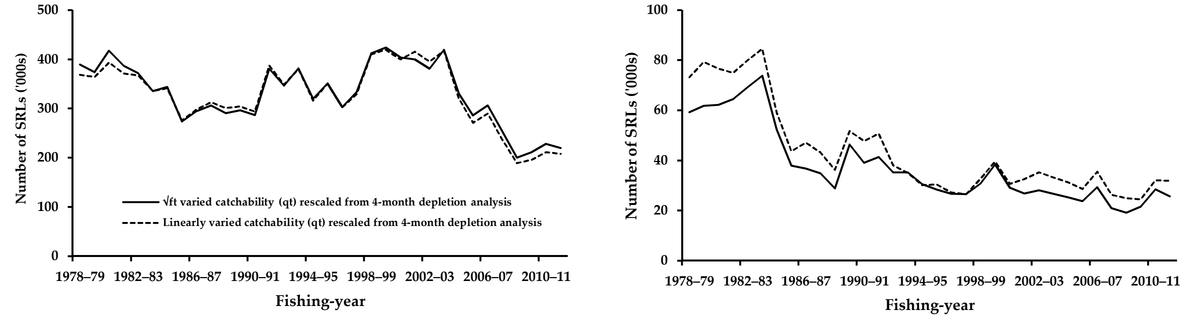


Figure 7. Results of analyses to determine trends in catchability for sexes combined over 34 fishing-years from 1978–79 to 2011–12 in the Western Zone (left) and Eastern Zone (right)

SRL, southern rock lobster; WZ, Western Zone; EZ, Eastern Zone; trends are shown for monthly standardised-CPUE (no per potlift) against cummulative catch for 4-month period February–May (a) and (b), for standardised effort (f_t and $\sqrt{f_t}$) and catchability q_t (both rescaled with geometric mean of 1) (c and d), and for unadjusted and adjusted standardised CPUE (e and f), and estimated population size at the start of February (g and h). Monthly catches and standardised CPUE are from Tables 1 and 2; The estimation models allow catchability q_t to vary linearly with fishing-year t or relative to fishing effort (ft) rescaled to give a geometric mean of 1.

Evidence of large-scale spatial declines in recruitment patterns of southern rock lobster *Jasus edwardsii*, across south-eastern Australia

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Abstract

Over the past 8−9 fishing seasons, recruitment has declined in all of the major rock lobster (*Jasus edwardsii*) fisheries in south-eastern Australia. This has translated into declines in commercial catch rates. In some regions, this decline has been rapid. For example, catch rate in the Southern Zone fishery of South Australia has decreased by 65% from to 2.1 kg/potlift in 2002 to 0.73 kg/potlift in 2008. While trends in recruitment and catch rate are spatially similar, contrasting regional signals are observed from puerulus settlement data which are used to predict future recruitment. Settlement has generally decreased in Tasmania, but some of the highest settlements on record were recorded in 2005 and 2006 in South Australia and Victoria. While historical management decisions may have contributed to the current status of rock lobster fisheries in some areas, simultaneous patterns of decline indicates possible large-scale environmental influences. Specific environmental factors remain largely unknown. However, we present data from an exceptional coldwater upwelling event observed during 2008 which suggests that growth rates in South Australia were significantly impacted. Overall, the results highlight the need for conservative TACCs in fisheries across south-eastern Australia in order to protect existing biomass and sustain rock lobster resources.

Introduction

Southern rock lobster *Jasus edwardsii* are distributed around southern mainland Australia, Tasmania and New Zealand (Phillips, 2006). They are primarily found in limestone reef systems or isolated granite formations that provide ideal lobster habitat in the form of protective crevices or ledges. In south-eastern Australia, the resource supports important regional fisheries across the States of South Australia, Victoria and Tasmania (Fig. 1). The total annual catch ranges from 3,500−4,000 tonnes with an estimated gross commercial value of ~AUS$200 million (Knight and Tsolas, 2009). Fishing methods have not changed markedly over time and generally consist of baited pots that are set individually overnight and hauled at first light.

All three fisheries are managed under management plans that have been separately developed under State legislation within each jurisdiction. Despite this, the management tools utilised are broadly similar across each region. These include input controls such as limited entry to the fishery, gear limitations and spatial or temporal closures, as well as output controls in the form of minimum legal sizes (MLSs) and total allowable commercial catches (TACCs). The fishery in each State is further sub-divided into various management zones that allow for known spatial differences in the biological characteristics of *J. edwardsii*. For example, MLSs can vary both between and within States in order to account for spatial differences in growth rate which ultimately impact on size of maturity (Hobday and Ryan, 1997; Gardner et al., 2006; Linnane et al., 2008).

Annual TACC decisions in each State rely heavily on stock assessment reports that provide information on the catch rate of both legal and undersized (pre-recruit) lobsters. These indicators are largely estimated from fishery-dependent data derived from commercial logbooks which became mandatory across south-eastern Australia during the 1970s. In addition, quota management controls are also influenced by outputs from stock assessment models that have been specifically developed for these fisheries (Punt and Kennedy, 1997; McGarvey et al., 1997). More recently, a single length-frequency based model (LenMod) has been developed and adopted by each State for the purpose of management advice (Gardner and Ziegler, 2010; Linnane et al., 2009a, b). Outputs typically include regional estimates of biomass, exploitation rate and recruitment.

Puerulus monitoring has been undertaken in south-eastern Australia since the early 1970s. Initially, puerulus research was driven by the twin aims of understanding both long-term settlement trends and early life history morphology. However, more quantified estimates of settlement developed in the 1990s (Prescott et al., 1996), fuelled by the success in Western Australia of utilising puerulus settlement indices for *Panulirus cygnus* to predict future recruitment to the fishable biomass (Phillips, 1986; Caputi et al., 1995). An emerging settlement-recruitment relationship also appears evident in *J. edwardsii,* namely in Tasmania (Gardner et al., 2001) and

New Zealand (Booth and McKenzie, 2009). In both species, it has been shown that future commercial catches can be successfully predicted from settlement indices using a 3–7 year time lag depending on the fishing region.

This study stems from growing concerns among scientists, fishery managers and members of the commercial fishing industry as to the status of rock lobster fisheries across south-eastern Australia. Specifically, stock assessment reports from South Australia, Victoria and Tasmania have highlighted declines in fishery performance indices across the region over recent seasons (Gardner and Ziegler 2010; Hobday and Morison, 2006; Linnane et al., 2009a, 2009b). Thus, the aim is to compare temporal and spatial trends in model-estimated recruitment, fishery-dependent commercial catch rate and puerulus settlement indices across all three States with a view towards a large-scale spatial analyses of the *J. edwardsii* resource across south-eastern Australia. Given the widespread declines in fishery performance indices, the study also focuses on the potential of environmental conditions to affect lobster populations. Specifically, we provide data from South Australia which suggests that an exceptional upwelling event may have impacted on lobster growth rates within the region.

Methodology

Management regions

The South Australian rock lobster fishery is divided into two regions for management purposes: a northern zone (NZ) and a southern zone (SZ) (Fig. 1). The NZ is by far the larger of the two covering an area of ~207,000 km^2 and extending from the mouth of the Murray River in the Coorong region of South Australia to the Western Australian border. The SZ extends from the Coorong to the Victorian border. Both zones are further sub-divided into Marine Fishing Areas (MFAs) for spatial analyses. The fishery in Victorian waters is also divided into two separately managed fishing zones: the Western Zone (WZ) (from the South Australian border to Apollo Bay) and the Eastern Zone (EZ) (from Apollo Bay to the New South Wales border). Tasmania has eight Stock Assessment Areas (SAAs). For the purpose of this study, the regions have been grouped into "North" (SAAs 3, 4, 5 and 6) and "South "SAAs 1, 2, 7 and 8) (Fig. 1). Given the close geographical proximity of the South Australian and Victorian fisheries, results from these regions are presented together while Tasmanian indices are provided separately.

Recruitment outputs

Annual recruitment estimates are one of numerous outputs generated by the length-structured stock assessment model (LenMod) which is now utilised across South Australia, Victoria and Tasmania. In summary, the model is based on lobsters in length bins growing, using estimated transition probabilities, into bins of equal or larger body size. Growth transition probabilities were estimated from lobster single tag-recovery experiments (McGarvey and Feenstra, 2001; Punt et al., 1997). Movement of lobsters and variations in catchability by season, sex, length, or region are accounted for as well as fishery selectivity.

The model is conditioned on catch in weight, and fitted to data on catch per unit effort (CPUE) by a monthly model time-step (which differs among States), commercial catch in number, tag-recapture information of movement among zones, and sample capture proportions by length bin and sex (Table 1). Each State has tailored the model to specific data sets and fishery regulations in each management zone, but, in general, the total number of lobsters entering the smallest size-class considered in the model each year, y (annual 'recruitment') in each subregion, s, is an estimated parameter $R[y,s]$ using the equation:

$$R[y,s] = \bar{R}[\mathrm{s}]\exp(\varepsilon[\mathrm{y},\mathrm{s}] - \frac{\sigma_R^2}{2})$$

where $\bar{R}[\mathrm{s}]$ is the mean (time-independent) recruitment level in each subregion, $\varepsilon[\mathrm{y}, s]$ is the estimated yearly log-deviation of recruitment about the mean, and σ_R is a pre-specified standard deviation. The value of σ_R determines the strength of a constraint imposed on the extent to which recruitment fluctuates among years. Recruitment is also bias-corrected so that the expected value of $R[y,s]$ is $\bar{R}[\mathrm{s}]$.

Commercial catch and effort

Daily mandatory commercial logbooks have generally been in place in each State since the 1970s. The data recorded are broadly similar across regions and includes information on catch by weight (kg) and number, number of pots set and location of fishing by subregion. Data are used to generate regional estimates of CPUE as kg of legally sized lobsters landed per potlift.

Puerulus monitoring

Seasonal patterns of settlement within each region were identified through monthly counts of puerulus in collector sites across the three States. The collectors are similar in design to those described by Booth and Tarring (1986), consisting of angled wooden slats that mimic natural crevice habitat. Monthly inspections involved a diver placing mesh bags around the collectors before they were hauled to the surface for cleaning and collection of puerulus. Five collector sites are located between Port McDonnell and Cape Jaffa in the SZ of South Australia (Fig. 1). Two collector sites are located on each of the Yorke and Eyre Peninsulas in the NZ. In Victoria, data on puerulus settlement were analysed from the Port Campbell site located in the WZ. In Tasmania, trends were analysed from three sites located at Bicheno (SAA 3), Iron Pot (SAA 2), and Recherche Bay (SAA 1). An annual puerulus settlement index (PSI) was calculated as the mean number of puerulus per collector in each site.

Temperature data

Bottom temperature data have been recorded at a fixed monitoring site off Southend in the SZ since 1998. The station consists of a StowAway TidbiT temperature logger attached to an anchored mooring with a surface marker buoy. The station records data at hourly intervals throughout the rock lobster fishing season which in the SZ extends from October 1st to May 31st of the following year. The logger is retrieved and the temperature data download at monthly intervals.

Temporal comparisons of lobster growth

Temporal changes in lobster growth were examined in the SZ rock lobster fishery of South Australia only. Growth rates were compared between two tag-recovery programs. The first involved using recaptures from a movement study undertaken from 1993−1996 across the fishery (Linnane et al., 2005). The second utilised tag returns from an ongoing annual fishery-independent monitoring survey from 2006−2009. Mean yearly growth of male and female lobsters, as von Bertalanffy functions of body length, were obtained using the GROTAG estimator of Francis (1988). GROTAG applies a maximum likelihood method to a re-parameterised form of the von Bertalanffy growth curve. The GROTAG parameters, g_α and g_β, quantify the rate of yearly growth at two selected carapace lengths, α = 100 mm CL for both sexes, and β = 120 or 140 mm CL, for females and males, respectively.

To quantify variation in growth estimates over time, subsets of tag recoveries which fell within a 2-year window were selected using lobsters tagged and released in the first year and recaptured in the second. Assuming an annual moult cycle, this assured that all lobsters had undertaken at least one moult during the study period. Minimum and maximum times-at-large for the lobster recaptures used in the growth analysis were 122 and 601 days. An examination of the initial-fit residuals found that nearly all the large residuals were negative, indicating they were from recaptured lobsters that grew less than the model-predicted mean growth increment. As a result, a data filter was implemented, which removed recaptures if the observed growth increment was less than half (or more than double) the predicted mean. This resulted in 10% and 22% of males and females being removed from the sample respectively. Final growth estimates were obtained using the filtered tag-recovery data sets.

Results

Recruitment trends

Trends in recruitment indicate large-scale spatial declines across almost all of the major rock lobster fisheries of south-eastern Australia over the past 8−9 seasons (Fig. 2). In South Australia and Victoria, highest levels of recruitment were observed in the SZ fishery where levels of recruitment increased from 1996 to 1999. Over the next eight seasons recruitment declined to pre 1997 levels, however, the estimate of ~2 million lobsters in 2007 is the lowest on record and represents a 49% decrease in overall recruitment since 1999 (3.9 million). Similar declining trends were observed in the NZ of South Australia and WZ fishery of Victoria over the same time period.

Recruitment has also decreased in Tasmania since the late 1990s, with the exception of two spikes in 2001 and 2005 in the southern region. Recruitment in Northern Tasmania has decreased from 1.9 million lobsters in 1997 to 0.61 million in 2007, an overall reduction of 68%. The estimates of recruitment for 2007 in both regions of Tasmania are the lowest on record.

Commercial catch rates

Recent decreases in recruitment levels have translated to declines in commercial catch rates in most fisheries across South Australia and Victoria (Fig. 3). In some regions, these declines have been rapid. For example, CPUE in the SZ fishery of South Australia increased from 0.93 kg/potlift in 1996 to 2.1 kg/potlift in 2002. However, over the next six seasons catch rate decreased by 65% to 0.73 kg/potlift, the lowest on record since 1978. Similar rates of decline were observed over the same time-scale in the NZ fishery of South Australia and the WZ of Victoria.

Declines in CPUE in recent seasons in Tasmania, have not been as rapid as in other regions. CPUE in southern Tasmania generally increased between the mid 1990s, with the 2008 estimate of 1.0 kg/potlift representing a 25% increase from 1994 (0.75 kg/potlft). Similarly, CPUE in Northern Tasmania increased from 0.82 kg/potlift in 1995 to 1.24 kg/potlift in 2002. Since then however, CPUE has decreased in this region and in 2008 it was 1.1 kg/potlift, a decrease of 11% from 2002. Despite not experiencing the rapid declines in CPUE observed in South Australia and Victoria, current catch rate estimates in both regions of Tasmania are low in relation to historical data.

Puerulus settlement

While trends in recruitment and catch rate were broadly similar all States, trends in puerulus settlement data were variable (Fig. 4). Nonetheless, there were some general similarities between sites. Peaks in puerulus settlement were observed in the SZ of South Australia and Bicheno, Tasmania in 1995. Similarly, common peaks in settlement were observed across the SZ and NZ of South Australia, WZ of Victoria and Recherche and Bicheno sites of Tasmania in 2002 and 2006.

Overall, there is some evidence to indicate that settlement in recent seasons at the Bicheno and Iron Pot sites in Tasmania has been lower than historical estimates For example, the average settlement at Bicheno from 1991–1999 was 6.0 puerulus/collector compared to 2.2 puerulus/collector from 2000−2008. Similarly, settlement at Iron Pot was on average 2.0 puerulus/collector through the 1990s compared to 1.0 puerulus/collector over the last eight seasons.

Across South Australia and Victoria, puerulus settlement tends to be consistently highest in the SZ fishery. In contrast to Tasmania, however, some of the highest settlement indices in South Australia and Victoria have been observed in recent seasons with no evidence to suggest that settlement trends are decreasing. For example, settlements in 2005 and 2006 were historically high for all three areas; the 2006 and 2007 settlement indices of 5 and 1 puerulus/collector were the highest on record for the SZ and WZ regions respectively.

Temperature data

Temperature profiles from the 1999/00 and 2007/08 rock lobster fishing seasons in the SZ rock lobster fishery of South Australia are compared in Fig. 5. The 1999 season data represents the more typical seasonal upwelling occurrence described by Lewis (1981) where bottom temperatures periodically drop below 12 °C during the December–March period. However, an exceptionally strong upwelling event occurred during the 2007/08 fishing season. From mid December of 2007, temperatures fell over a two-month period from 15.6 °C to 9.4 °C by mid-February of 2008 before increasing thereafter. Bottom temperatures were below 12 °C throughout February of 2008. As a result, the 2007/08 upwelling event was significant in terms of its intensity and duration.

Temporal comparisons of lobster growth

Growth rates of both male and female lobsters in the SZ fishery of South Australia have decreased over time (Fig. 6). This is particularly evident for males of both 100 and 140 mm carapace length (CL), where mean predicted growth from 2006/07–2008/09 was lower by ~3−4 mm CL compared to 1994/95 and 1995/96 estimates. Similarly, mean predicted female growth of 100 mm CL and 120 mm CL size classes were lower in 2007/08 and 2008/09 compared to estimates from 1994/95−1996/97. Interestingly, the lowest mean growth for males of both size classes was observed in 2007/08, coincident with the significant upwelling event of the same season (Fig. 5).

Discussion

A TACC limit is the primary tool used across South Australia, Victoria and Tasmania as a means of managing southern rock lobster resources. Underpinning annual TACC decisions are stock assessments that report on key biological performance indicators that are generally linked to specific decision making rules within the fishery Management Plans for each State. As a result, the recent declines in recruitment and subsequent commercial catch rate trends have led to significant TACC cuts in all of the fisheries across south-eastern Australia. For example, in the Northern Zone of South Australia, the 625 tonne TACC introduced in 2003/04 has been gradually cut to 310 tonnes for the 2009/10 season (Fig. 7). Similarly, the Southern Zone TACC has been reduced from 1,900 tonnes to 1,400 over the same period. In Victoria, the Western Zone TACC has been gradually reduced from 450 tonnes in 2006/07 to 240 tonnes for the 2009/10 season. The Eastern zone has had a marginal increase from 60 tonnes set in 2006/07 to 66 tonnes for the 2009/10 season. In Tasmania, the TACC has been cut from 1,523 tonnes in 2008/09 to 1,323 tonnes for the 2010/11 season. It is envisaged that further reductions will see the Tasmanian TACC gradually reduced to 1,193 tonnes by 2012/13. Despite these widespread reductions, there is no clear evidence to date to suggest that the declines in CPUE are being arrested or that catch rates are being stabilised in any fishery.

The factors driving the declines in fishery performance across south-eastern Australia have been the focus of much debate. In some areas at least, there is strong evidence to suggest that historical management decisions have contributed to the current status of specific regions. For example, a TACC was not introduced into the Northern Zone fishery of South Australia until the 2003/04 season, despite the fact that catch decreased by 49% from 1,001 in 1999/00 to 503 tonnes in 2003/04 and catch rate decreased by 47.5% from 1.43 kg/potlift to 0.75 kg/potlift, over the same period (Linnane et al., 2009b). Despite a TACC of 625 tonnes, only 503 tonnes were caught in 2003/04. The TACC was subsequently reduced to 520 tonnes for 2004/05 (446 tonnes landed) and to 470 tonnes for 2008/09 (403 tonnes landed) with 2009/10 being the first season where the TACC of 310 tonnes was set below the previous years catch.

The spatial dynamics of the rock lobster fishing fleet within each of the State fisheries is also worth consideration in relation to recent downturns. In each fishery, approximately 70−80% of the annual catch is taken within inshore waters (<60 m depth) despite the fact that higher catch rates can be achieved in offshore grounds (Linnane and Crosthwaite, 2009). Such fishing behaviour is in response to Asian market forces, which for cultural reasons, prefer “small” (<1 kg) dark red coloured lobsters (Chandrapavan et al., 2009). These individuals are mainly found in shallow depths, while offshore (>60 m) lobsters tend to be paler in colour. As a result of higher unit prices being offered for dark red lobsters, fishing effort has contracted inshore as fishers attempt to maximise their economic return under the TACC system. Given the downturn observed across all States, there is therefore cause to question if current fleet dynamics have led to hyperdepletion (Hilborn and Walters, 1992) i.e. the appearance that stock size has declined much more than it actually has as a result of inshore targeting. However, it is worth noting that analyses of both fishery dependent and independent data in South Australia have identified decreases in catch rate across all depth ranges in the fishery (Fig. 8 and Linnane et al., 2009a).

In addition to fishing dynamics, increases in effective effort across all regions were significant through the 1970s, 80s and 90s (Baelde 2001). Specifically, the introduction of global positioning systems (GPS), advanced hydro-acoustic equipment, radar and the shift away from displacement to planing hulled vessels mean that catch rates are likely to have been impacted by increased levels of fishing efficiency. While changes in effective effort are difficult to quantify, there is strong evidence of spatial expansion and localised depletion in the NZ fishery of South Australia, driven by the update of GPS technology during the 1980s (Linnane et al., 2009b). Overall, this resulted in a hyperstabilisation scenario where fleet expansion maintained high catch rates thus masking declines in overall lobster abundance. However, it is worth noting that GPS technology had become fully operational on almost all Australian commercial fishing vessels by the mid 1990s (Baelde 2001), suggesting that factors, other than fishing pressure alone, may be contributing to the more recent observed downturns in fishery performance across south-eastern Australia.

The widespread nature of the decline, combined with broad-scale similarities in puerulus settlement trends, point towards possible large-scale environmental factors. Studies on the impacts of oceanographic or environmental conditions on *J. edwardsii* recruitment remain limited. However, there are indications to suggest that they are substantial. The Bonney upwelling system of South Australia is part of a larger upwelling system that extends from the western Bass Strait to the eastern Great Australian Bight (Lewis, 1981; McClatchie et al., 2006). During summer (December−February) the predominant south-easterly winds result in an upwelling of nutrient-rich, cold water (11−12 ºC) which intrudes onto the continental shelf across the Southern Zone rock lobster fishery region. While annual upwelling events are variable in duration and intensity, sub-surface temperatures do not generally fall below 11 °C (Lewis, 1981). As a result, the 2008 upwelling, where temperatures at 60 m depth decreased to 9.2 °C in February, is considered to be a historically exceptional event. However, the impacts of extreme environmental conditions on rock lobster survival and growth remain limited to laboratory studies, with the emphasis focused on optimum temperature regimes for commercial culture (Crear et al., 2000; Johnson et al., 2008). Growth rates and size of maturity estimates (SOM) in *J. edwardsii* generally decrease with decreasing water temperature (Hobday and Ryan, 1997; Gardner et al., 2006; Linnane et al., 2008). This supports our preliminary findings which suggest that growth rates of tagged adults were reduced in response to the extreme upwelling event of 2008, but what impact the rapid temperatures decrease had on puerulus, post-puerulus or juvenile stages survival and growth remains unknown. Similar reductions in growth rate and subsequent recruitment in response to a large-scale environmental perturbation have been observed in *Jasus lalandii* in South Africa (Pollack et al., 1997). Finally, it is worth noting that under climate change scenarios, upwelling events are expected to increase globally (Bakun, 1990). While current climate models do not indicate a drastic change in winds in the region of the Bonney coast, recent increases in south-easterly winds during the summer months indicate that some alteration in strength or frequency of the upwelling is not implausible (McInnes et al., 2007). It is essential that future research focuses on the physiological impacts of extreme coldwater event on all life stages of *J. edwardsii* if extreme upwelling events such as those experienced during the 2007/08 season are to become more frequent in nature.

Pecl et al. (2009) have also highlighted the potential vulnerability of southern rock lobster to climate change impacts. They suggest that increased southward penetration of the warmer Eastern Australian Current down the east coast of Tasmania (Ridgway, 2007) will likely lead to north-eastern and eastern regions of the State experiencing continued declines in puerulus settlement. As a result, recruitment of rock lobster may become more variable with time in addition to generally declining. This will ultimately lead to lower catch rates within the commercial fishing sector.

In addition to recruitment, there is also evidence to suggest that puerulus settlement has declined along the east coast of Tasmania. The links between oceanographic and environmental effects on puerulus settlement are well documented in the western Australian rock lobster *Palinurus cygnus*. Specifically, the strength of the Leeuwin Current, combined with westerly winds, is highly correlated with puerulus settlement (Pearce and Phillips, 1988; Caputi, 2008). This in turn has revealed a correlation between temporal variations in settlement and changes in the El Nino Southern Oscillation (ENSO) index (Clarke and Li, 2004). In particular, as shelf edge flows weaken during El Nino years, puerulus survival is impacted through associated changes in water temperature, eddy structure and overall productivity. Interestingly however, low puerulus settlement observed in 2007/08 and 2008/09 in collector sites across Western Australia cannot be explained by environmental factors It is suggested that both short and long term environmental changes (physical and biological) occurring in the eastern Indian Ocean may be responsible (Brown, 2009).

While puerulus settlement appears to be decreasing in Tasmanian sites, declines in South Australia and Victoria are not apparent, with some of the highest settlements on record observed across both States during 2005, 2006 and 2007. Puerulus settlement, at least in South Australia, is correlated with the strength of north-westerly winds acting on physical oceanographic conditions (McGarvey and Matthews 2001). Specifically, strong alongshore wind stress, which is favourable to inshore puerulus settlement, correlates with increased settlement trends. However, while the environmental factors controlling settlement are broadly understood in south-eastern Australia, the relationship between puerulus settlement and recruitment to the commercial fishery is not clear. While some correlations have been shown to exist within certain regions of Tasmania (Gardner et al., 2001), the relationship dynamics and associated time lags remain variable elsewhere. Based on tag-recapture studies, the time taken by individuals to reach the minimum legal size of 98.5 mm carapace length in the Southern Zone of South Australia is ~5 years (McGarvey et al., 1999). As a result, it is expected that the exceptionally high puerulus settlement observed in 2005 and 2006 should translate into increased recruitment into the fishable biomass during the 2010/11 and 2011/12 seasons. However, it should be noted that the third highest settlement on record in the Southern Zone in 2002, did not translate into increased recruitment or subsequently higher catch rates during the 2007/08 season.

Given the decline is stock status with across south-eastern Australia, it is worth comparing current trends with those in regions further north within the New Zealand fishery. The New Zealand species is genetically identical to that found in south-eastern Australia (Smith et al., 1980) and supports a substantial fishery that yields annual catch in excess of 2,600 tonnes (Anon. 2009). The fishery is divided into 10 regions termed “CRAs” for management purposes. While fishery performance is variable across CRAs, the most recent report on the status of the resource does not suggest that major declines are occurring over the period observed in south-eastern Australia (Anon 2009). For example, the status of CRAs 6 and 8 located off the South Island and which combined yield a total commercial catch of ~1,300 tonnes, has increased markedly over the 2004–2008 seasons. Catch rates in CRA 6 have increased by ~30% over this period while those in CRA have doubled. In addition, there is no evidence from puerulus monitoring data in New Zealand to indicate that settlement patterns have decreased, at least over the last two decades (Booth and McKenzie, 2009). Overall, this suggests that the factors driving the declines in south-eastern Australia are spatially confined and are not impacting stocks within other regions.

Finally, it is important to consider the impacts of lobster declines on egg production within South Australia, Victoria and Tasmania to the overall south-eastern fishery. Bruce et al. (2007) through a combination of biological and hydrodynamic modelling, reported an overall easterly displacement of southern rock lobster larvae from southwest Western Australia to the east coast of Tasmania. The study identified the Southern Zone of South Australia as one of the most significant sources of settling puerulus for most of the south-east Australian fishery. The current study has highlighted that the Southern Zone region has the fastest declining catch rate having decreased by 65% since 2002. This has translated to a corresponding reduction in egg productions within the fishery (Linnane et al. 2010). Presumably, this translates to a decline in the number of ovigerous females contributing to larval production. Whether the declines in South Australia have impacted on easterly regions remains unknown. However, if the various State fisheries are connected by larval flows, this suggests careful management of key areas such as the South Australian Southern Zone is essential not just for localised areas but for the south-eastern fishery as a whole. Overall, given the levels of uncertainty surrounding the driving forces behind recent declines in fishery performance indices, the findings highlight the need for conservative TACCs across south-eastern Australia in order to protect existing biomass and sustain rock lobster resources.

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Table 1. Time steps, size-class widths and boundaries and model subregions for South Australia (NZ=Northern Zone, SZ=Southern Zone), Victoria, and Tasmania. Note: the specifications for each subregion are based on data availability and the differences in the values for biological parameters spatially.

Variable	South Australia	Victoria	Tasmania
# Time steps/year	8(NZ):9(SZ)	1	8
Size-class width (mm)	4	10(males):5(females)	5
Size-class lower boundary (mm)	82.5	80	60
Subregions	1(NZ):2(SZ)	6	8

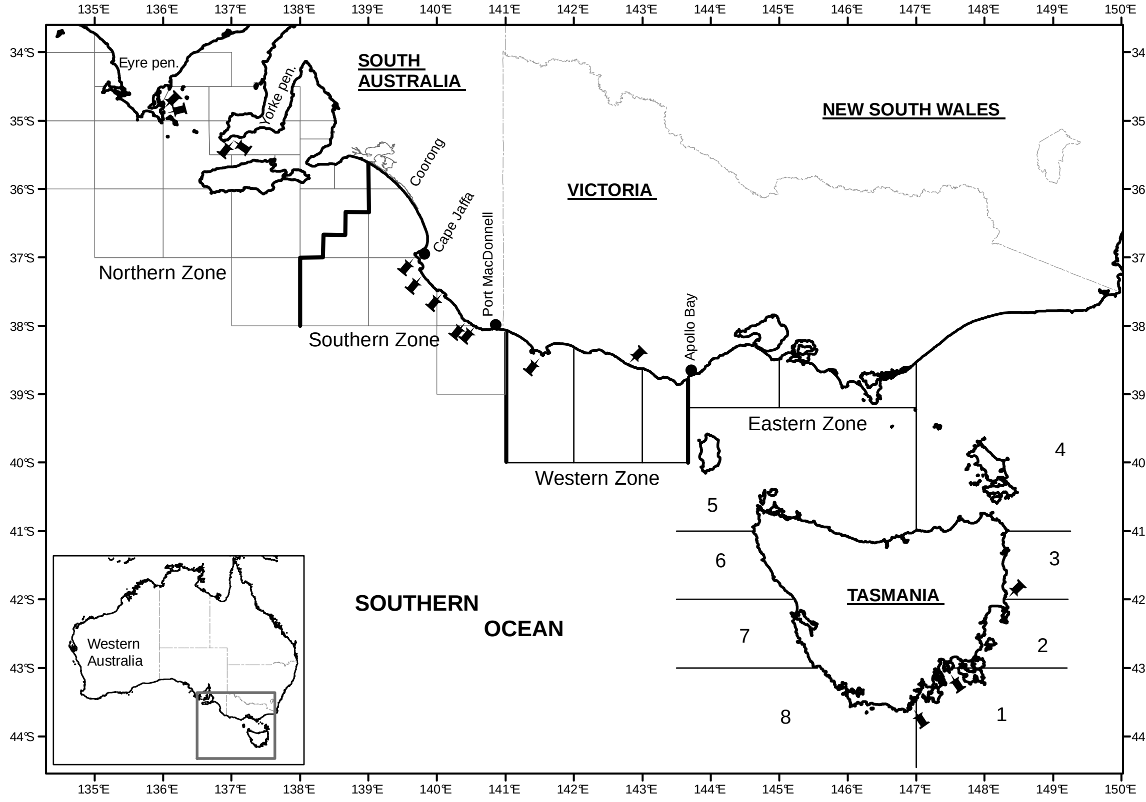
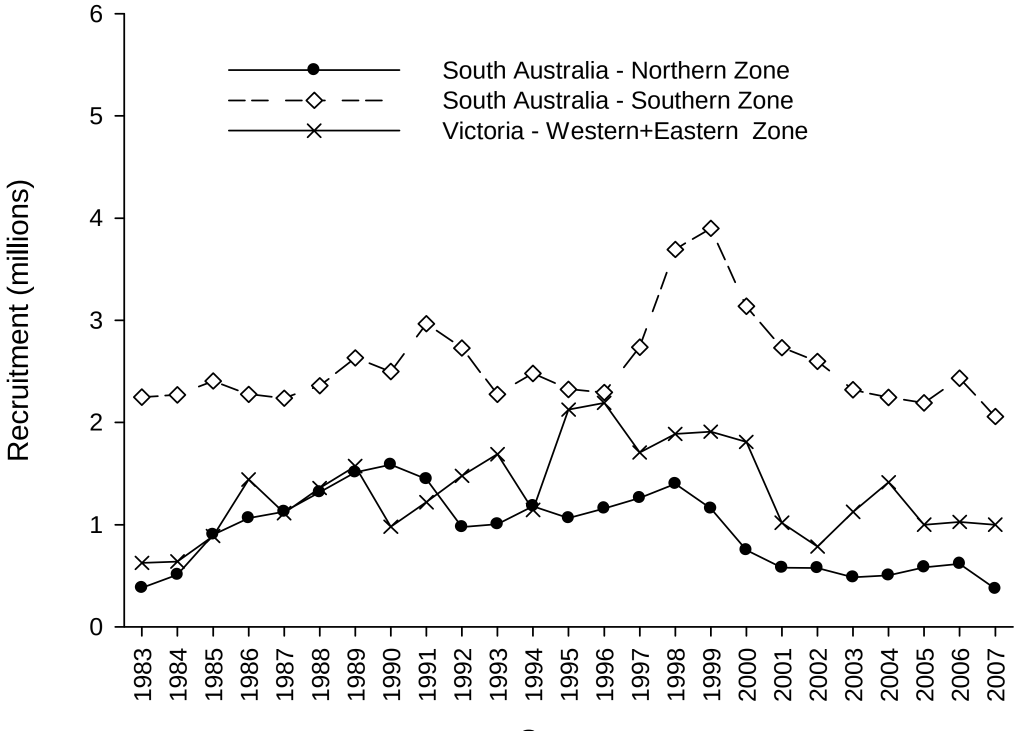


Figure 1. Location of rock lobster management regions across South Australia Victoria, and Tasmania. Symbols indicate location of puerulus monitoring sites.



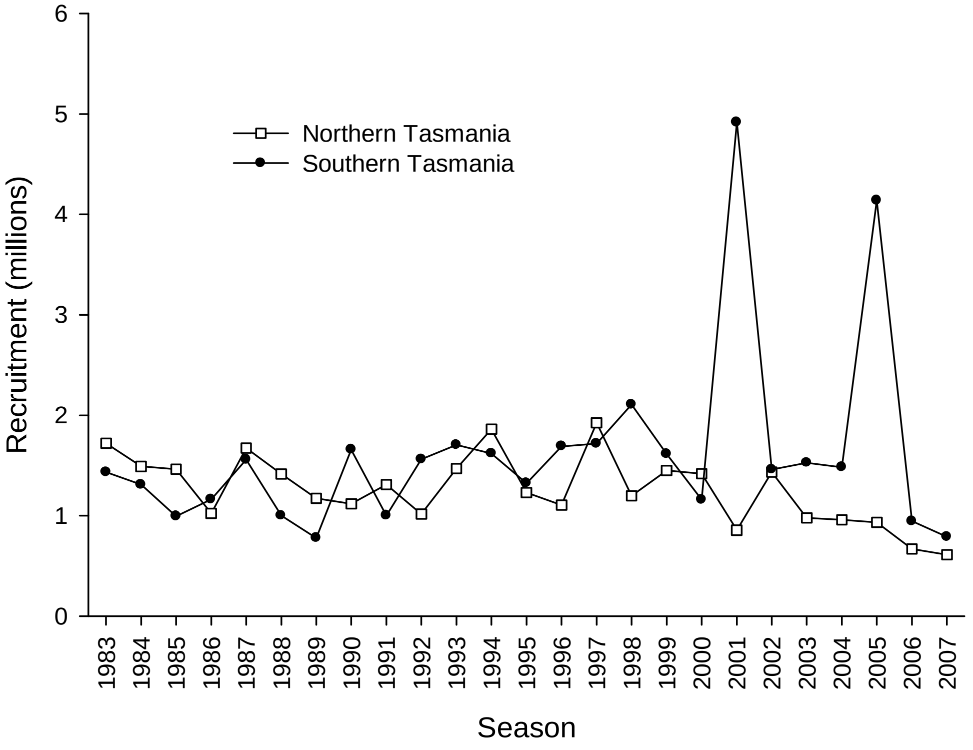


Figure 2 Trends in maximum likelihood estimates of recruitment across South Australia, Victoria (top) and Tasmania bottom from 1983 to 2007.

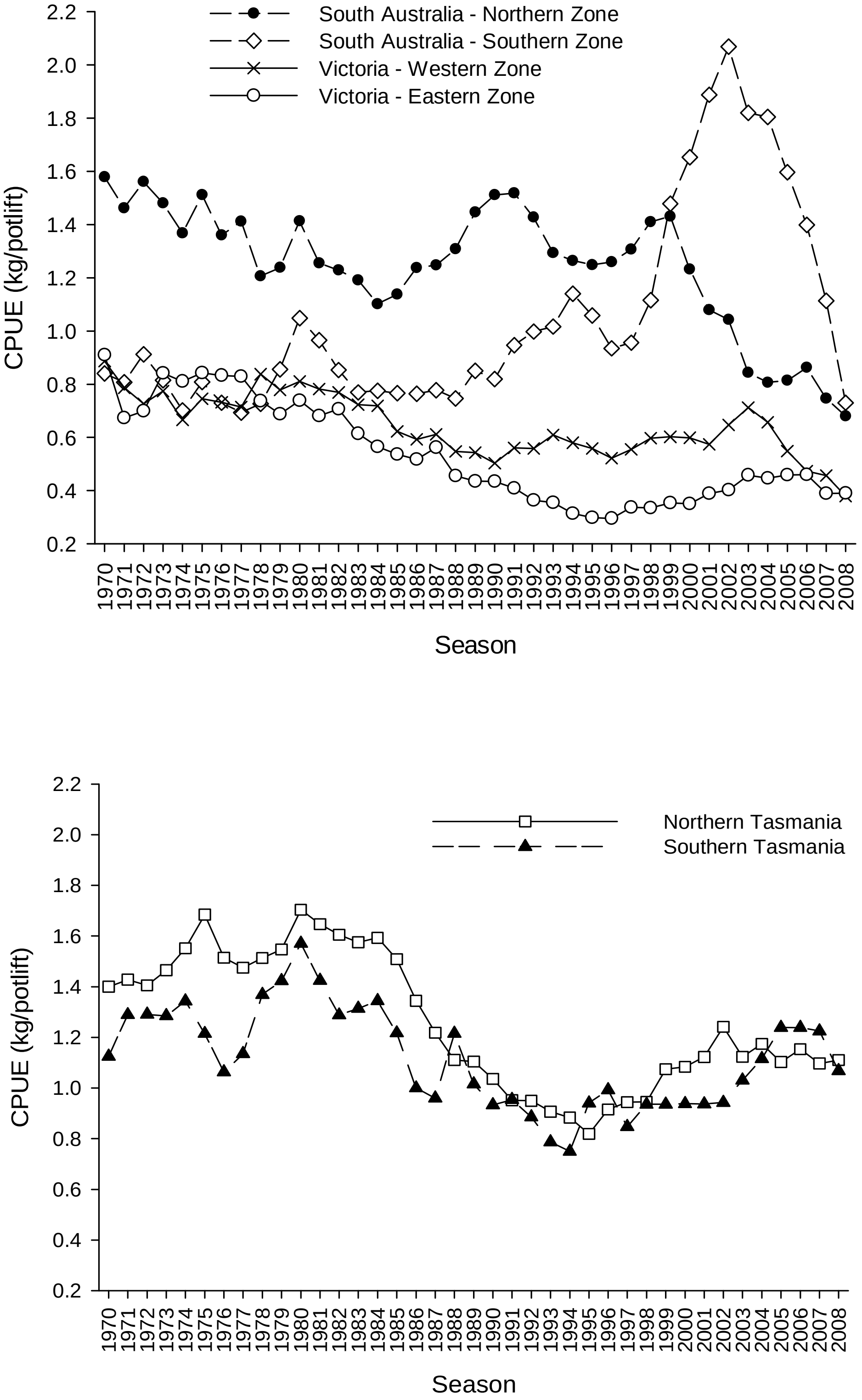
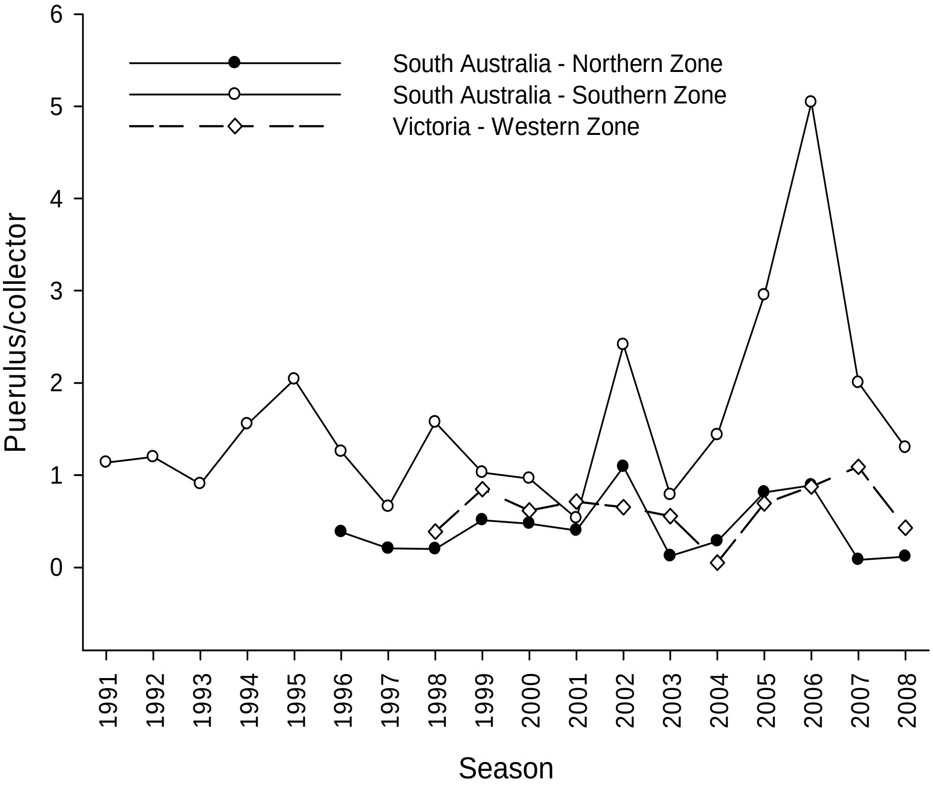


Figure 3 Trends in catch per unit effort (CPUE) across South Australia, Victoria (top) and Tasmania (bottom) from 1970 to 2008.



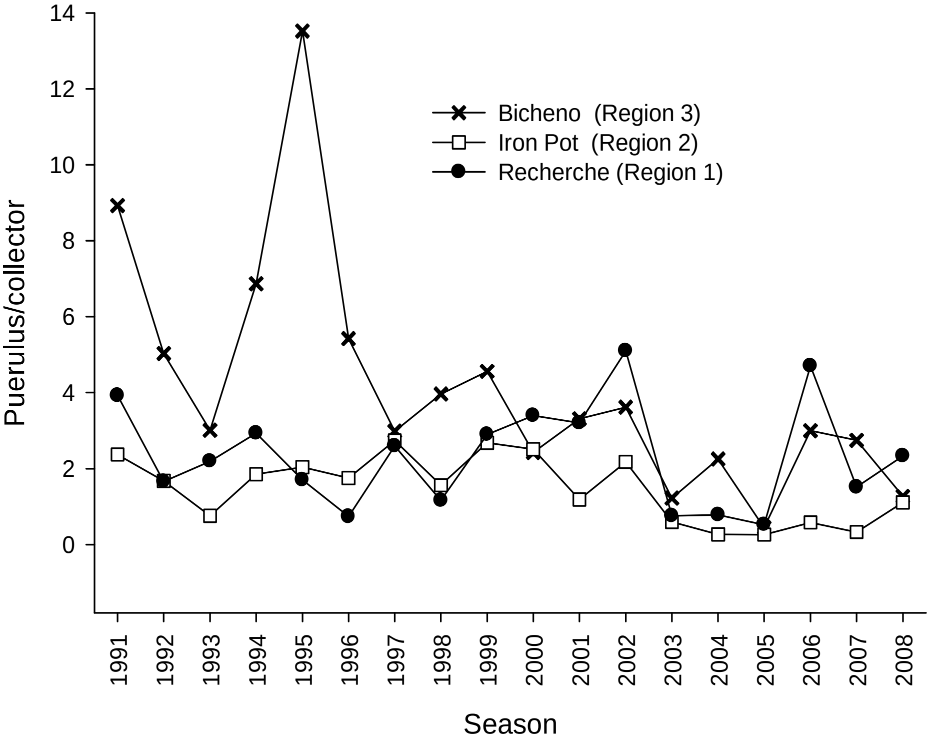


Figure 4 Trends in puerulus settlement across South Australia, Victoria (top) and Tasmania (bottom) from 1991 to 2008.

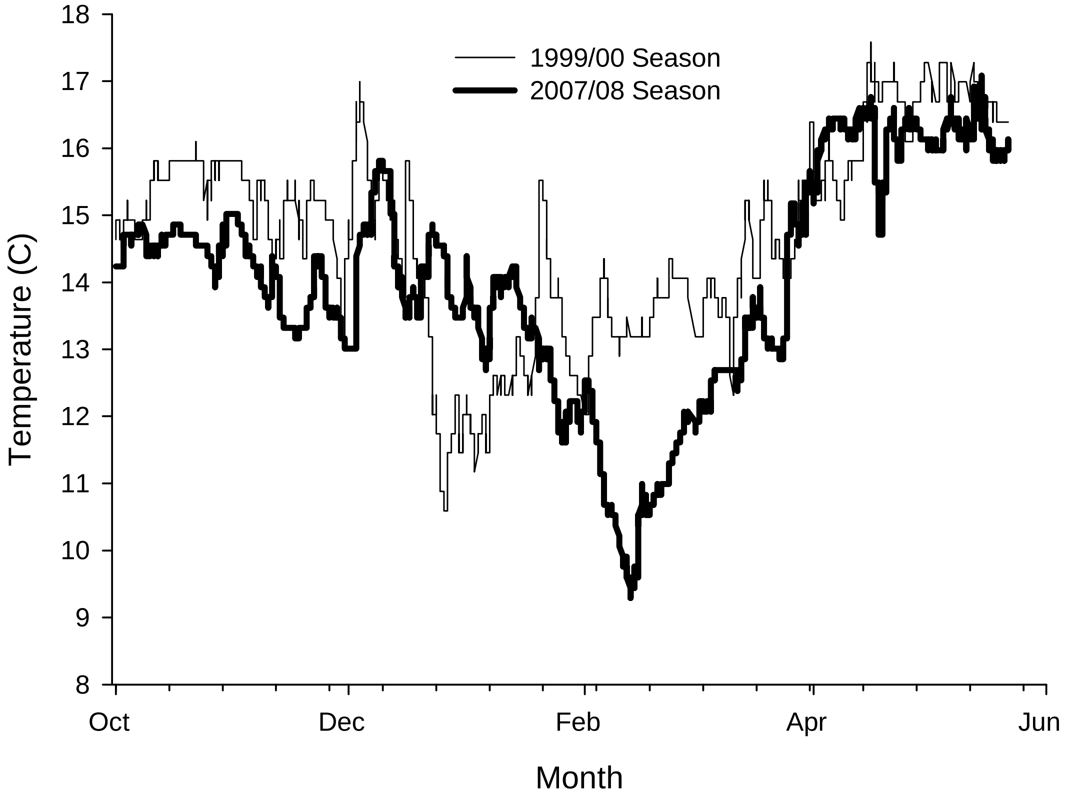


Figure 5. Comparison of temperature profiles at the fixed monitoring site located off Southend (60 m depth) in the SZ fishery of South Australia during the 1999/00 and 2007/08 rock lobster seasons.

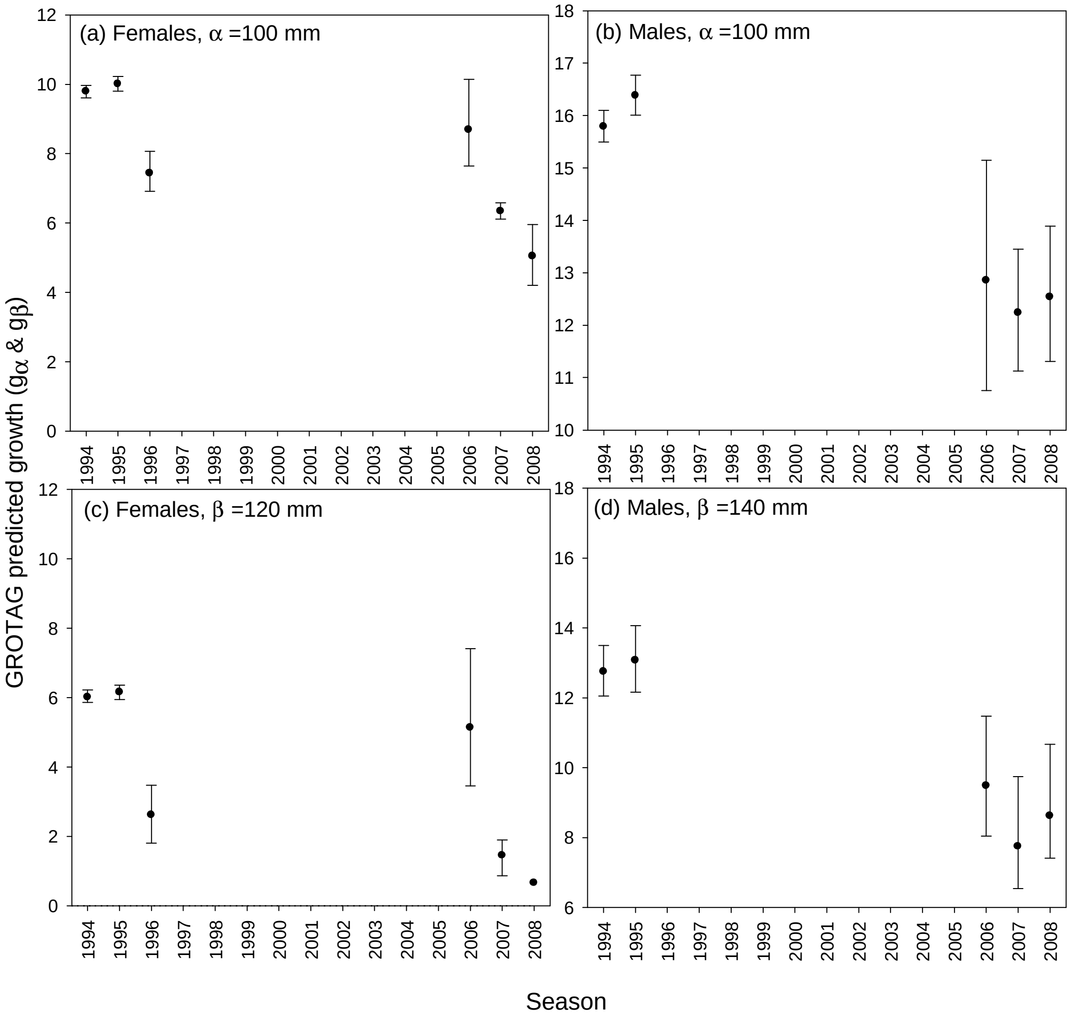


Figure 6. Temporal comparisons of growth in both male and female lobsters in the Southern Zone fishery of South Australia. Data represent the season in which the lobsters were recaptured (n = 3,877).

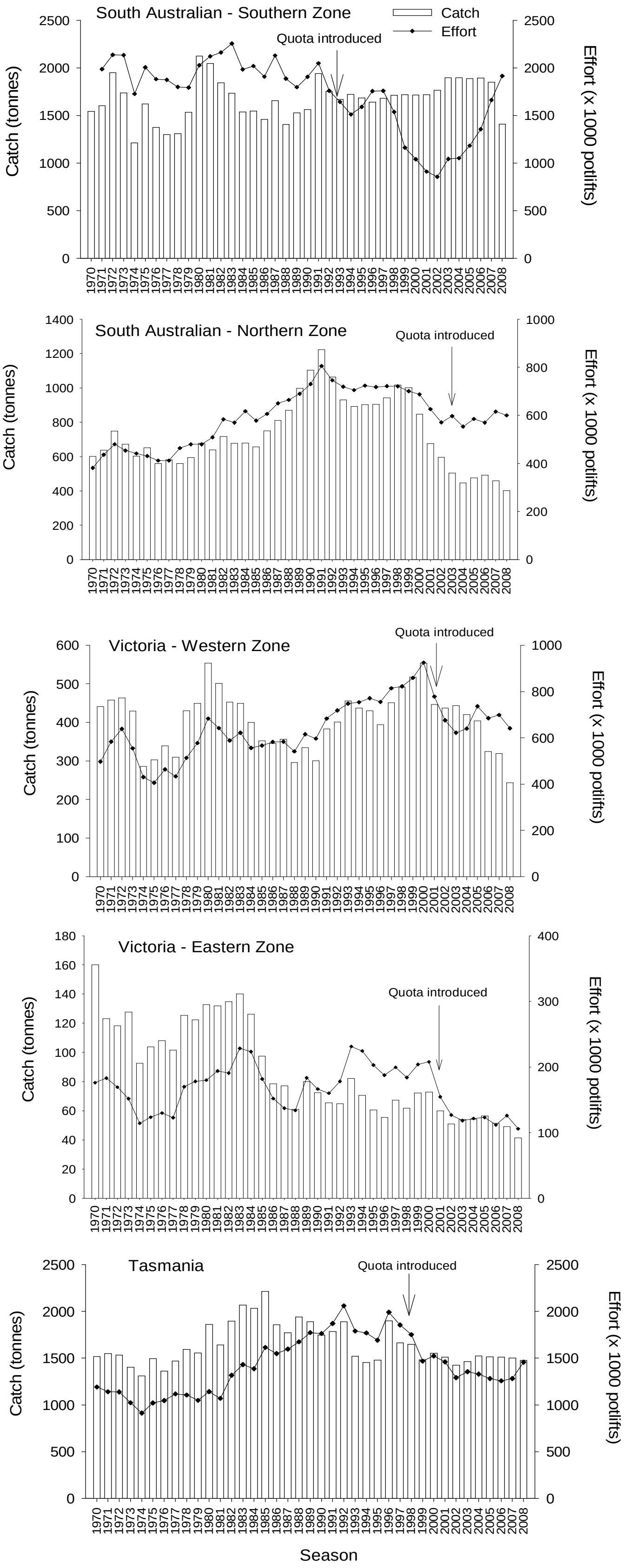


Figure 7. Catch and effort trends across South Australia, Victoria and Tasmania from 1970 to 2008.

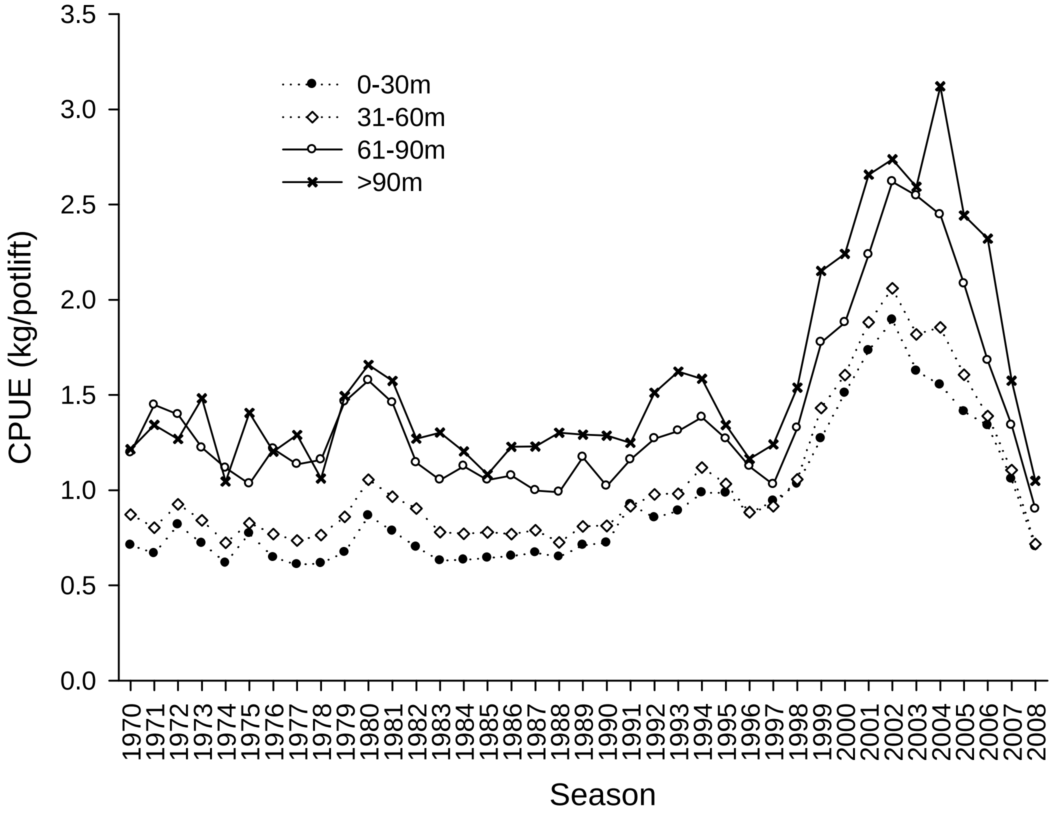


Figure 8. Catch per unit effort (CPUE) in four depth strata in the South Australian southern zone rock lobster fishery from 1970 to 2008 (adapted from Linnane and Crosthwaite 2009).

Examining the relationship between quantified puerulus settlement and fishery recruitment in the southern rock lobster (*Jasus edwardsii*) across south-eastern Australia

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Abstract

The southern rock lobster *Jasus edwardsii* supports important commercial fisheries in south-eastern Australia with monthly monitoring of puerulus settlement in sites across South Australia, Victoria and Tasmania undertaken since the early 1990s. Firstly, annual trends in settlement were spatially analysed across the three States. All South Australian and Victorian zones were positively correlated suggesting that settlement patterns between the two bordering States are closely related. In Tasmania, settlement sites along the northern eastern coast were positively correlated but showed no relationship with areas further south. Overall, annual Tasmanian settlement patterns were distinctively different from those in South Australia and Victoria. Secondly, annual indices in settlement were correlated with lagged estimates of model recruitment over various overlapping time periods. In South Australia, the strongest correlations between settlement and recruitment to minimum legal size were observed using a 4−5 year time lag. Within Victoria and Tasmania, the period from settlement to recruitment at 60 mm carapace length was two and three years respectively. Based on known growth rates of juveniles in these fisheries, it is estimated that the period from 60 mm to legal size is another 2−3 years suggesting that the total time from settlement to the fishery ranges from 4−6 years in these regions. Overall, the results indicate that puerulus monitoring is a relatively robust indicator of future fishery performance and should therefore be regarded as an important management tool for rock lobster resources within south-eastern Australia.

Introduction

Southern rock lobster *Jasus edwardsii* are distributed around southern mainland Australia, Tasmania and New Zealand. The reproductive cycle of the species is highly seasonal. Mating occurs between April and July, followed by a brooding period of 3−6 months before peak hatching in September/October (MacDiarmid 1989). Phyllosoma spend 12–24 months in offshore waters undergoing development through 11 larval stages (Booth and Phillips, 1994) before settling onto inshore reefs as juvenile puerulus (Kennedy *et al.* 1991; Booth 1994). Growth rates from puerulus to adult exhibit a high degree of geographical variation (McGarvey *et al.* 1999; Punt *et al.* 1997) and as a result, the size of sexual maturity also differs spatially (Hobday and Ryan 1997; Gardner *et al*. 2006; Linnane *et al*. 2008; 2009).

In Australia, the fishery for *J. edwardsii* is highly valued across the States of South Australia, Victoria and Tasmania with ~3000 tonnes landed annually at a commercial value of ~AUS$200 million (Knight and Tsolos, 2012). All three fisheries are managed using a total allowable commercial catch (TACC) quota system as well as a suite of input controls that include limited entry, closed seasons and gear restrictions. Annual quota allocations in each region rely heavily on the outcomes of annual stock assessments that analyse the catch rate of both legal and undersized (pre-recruit) individuals. In addition, quota management controls are also influenced by outputs from a number of stock assessment models that have been specifically developed for these fisheries (Punt and Kennedy 1997; McGarvey *et al*. 1997). Model outputs include historical estimates of recruitment that are largely driven by fishery dependent catch and effort data.

Puerulus monitoring has been undertaken across all three States since the early 1970s (Lewis 1977) but quantified estimates of settlement did not develop until the 1990s (Kennedy *et al.* 1991; Prescott *et al*. 1996). Initially, research was driven by the twin aims of understanding both long-term settlement trends and early life history biology. More recently, the focus has changed to examining the use of quantified puerulus settlement indices (PSI) as indicators of future recruitment to the fishable biomass. This largely stems from the success of this relationship in Western Australia where future commercial catches of *Panulirus cygnus* can be successfully predicted from settlement indices using a 3–4 year time lag (Phillips 1986; Caputi *et al*. 1995). Similar relationships have also emerged in specific regions of some *J. edwardsii* fisheries (Gardner *et al*. 2001; Booth and McKenzie 2009).

The aims of this study were to firstly examine the spatial trends in puerulus settlement across South Australia, Victoria and Tasmania. Secondly, we examined the relationship between settlement and subsequent recruitment into the fishery within each region under a range of time lags. Finally, the relationship between settlement and recruitment was used to project future estimates of exploitable biomass for one fishery zone in South Australia under a range of TACC scenarios.

Methods

Puerulus sites and sampling

In South Australia, data were analysed from five puerulus monitoring sites (Blackfellows Caves, Livingstones Bay, Beachport, Cape Jaffa and Kingston) in the Southern Zone and from four sites (Stenhouse Bay, Marion Bay, Maclaren Point and Taylor Island) located in the Northern Zone (Figure 1). In Victoria, data were analysed from two sites in the Western Zone fishery at Port Campbell and Apollo Bay while in Tasmania data from Recherche Bay, South Arm, Bicheno and Flinders Island were utilised.

Sampling consisted of monthly site inspections which involved a diver placing a mesh bag around each collector before they were hauled to the surface for cleaning and collection of pueruli. The collectors were similar in design to those described by Booth and Tarring (1986) consisting of angled wooden slats that mimic natural crevice habitat. An annual puerulus settlement index (PSI) was calculated as the mean number of puerulus per collector in each site. Annuals PSI values were calculated across calendar years for South Australia and Tasmania. In the case of Victoria, the fishing seasons from November to October were used. Due to certain years where not all months were sampled, an annual PSI value was only included for years where there were eight or more months sampled.

Recruitment to the fishery

The relationship between PSIs and recruitment was investigated from sampling periods between 1991 and 2010 under a range of time lags from 1 to 5 years. Estimates of recruitment to the fishery were derived from a length-based population dynamics model (Punt and Kennedy 1997; Hobday and Punt 2001) specifically designed for rock lobster fisheries in south-eastern Australia. The model is age-based and is conditioned on effort, with a Baranov total mortality rate and a Schaefer catch relationship. It fits to data on commercial catch rates, length-frequency of the catch and estimates of the annual catches in numbers. Parameters related to growth, natural mortality and selectivity are determined from auxiliary analyses (see Hobday and Punt 2001 for details). In South Australia, recruitment is estimated to the minimum legal sizes of 105 mm and 98.5 mm carapace length (CL) in the Northern and Southern zones respectively. It Victoria and Tasmania, recruitment is estimated to 60 mm CL.

In South Australia, PSI estimates from the Northern and Southern zones were compared with specific recruitment estimates from these regions. As puerulus sampling is not undertaken in the Eastern Zone of Victoria, recruitment estimates from this region were correlated with settlement trends from the Western Zone. Within Tasmania, PSIs were correlated with recruitment estimates from management sub-regions where puerulus sampling was undertaken (see Figure 1).

Data analyses

A standard Pearson's correlation coefficient (r) was used to analyse the relationship between PSI and model estimated recruitment. The significance level was based on a null-hypothesis for two-tailed Student t-test with n–2 degrees of freedom for n observations.

Future biomass estimates

Future estimates of biomass in South Australia's Northern Zone were generated using the qR model which has been used as part of the annual stock assessment for the fishery since 1997. A detailed description of the qR model is provided in McGarvey and Matthews (2001). In summary, the qR model is an age-based model with an annual time step fitting to annual catch in weight (kg) and in number of legal sized lobsters landed. Effort (number of commercial potlifts) is taken from logbook data and a Baranov survival model using a bilinear (Schaefer) catch relationship is assumed. The model likelihood is written as a modified normal and optimized numerically.

The qR model utilised puerulus settlement data to determine future recruitment over the period from 2012 to 2016 to assess future fishery trends under various harvest strategies. Several assumptions were made as part of this process. First, annual variation in mean forecasted qR recruitment was assumed to vary in linear proportion to puerulus settlement. Secondly, to convert from relative annual puerulus per collector, to absolute numbers of lobster reaching legal size four years later, the mean level of settlement was rescaled so that it equalled the mean level of qR recruitment over the overlapping data series years from 2000 to 2011. Finally, it was assumed that the annual variation about the mean level of recruitment in each year followed a lognormal distribution with a standard deviation that scaled in proportion to the computed standard error of the yearly estimate of annual settlement. Settlement index standard error was computed from the variation among the monthly puerulus per collector values used to estimate the annual settlement mean value. In total, a thousand recruitment time series, each with five forecasted years from 2012 to 2016, were then randomly sampled from this lognormal distribution and used as recruit number inputs for 1000 iterated qR model projection runs.

Results

Spatial trends in settlement

PSI estimates from all sites across South Australia, Victoria and Tasmania were analysed for spatial trends (Figure 2 and Table 1). In South Australia, both Southern and Northern Zone settlements trends were positively correlated as were the two sites of Port Campbell and Apollo Bay. Overall, with the exception of the Southern Zone and Apollo Bay, all South Australian and Victorian zones were positively correlated suggesting that settlement patterns between the two bordering States are closely related.

Analyses of PSIs among the four Tasmanian collector sites indicated a latitudinal trend in correlations (Table 1). Flinders Island, the most northerly site, was more closely correlated with the closest collector site of Bicheno to the south. Both Bicheno and Flinders Island were also positively correlated with South Arm, the next site south. However, these correlations got successively weaker at more southerly collection sites. In particular, PSIs from Recherche Bay, the most southerly site, did not correlate with any other site along the east coast of Tasmania. Given the strong positive correlation between as the two northerly sites of Flinders Island and Bicheno, this suggests that a coherent settlement rate signal is provided by monitoring in this northeast region of Tasmania. As a result, these two sites were aggregated as a measure of puerulus settlement from this Tasmanian region for analyses with future recruitment to the fishery.

None of the Tasmania sites were correlated with either the South Australian or Victorian settlement trends. Regarding the South Australian and Victorian PSIs, most notable were the synchronised spikes in PSI observed across all zones in 2002, 2005 and 2006 which were not observed in Tasmanian sites. Overall, these results indicate that South Australian and Victorian settlement patterns are broadly similar but are unrelated to trends observed in Tasmania.

Correlations between puerulus settlement and recruitment

South Australia

In the Northern Zone, PSI and recruitment to the minimum legal size (MLS) of 105 mm carapace length (CL) were positively correlated by a lag period of four years using the overlapping time period from 1996−2006 (Figure 3, Table 2).

In the Southern Zone, PSI and recruitment were not positively correlated over the complete overlapping period from 1996−2005. However, it is worth noting that in more recent seasons, from 2002−2005 (recruitment years 2007−2010), the variables were positively correlated using a five year lag ($R = 0.87$), however low n values prevent testing for significance. Southern Zone PSI was also significantly correlated with Northern Zone recruitment using a 4-year time lag.

Victoria

Settlement trends in both sampling sites from Apollo Bay and Port Campbell were positively correlated over the thirteen year sampling period from 1998–2010 (Figure 3, Table 3). Testing of various time periods between settlement and recruitment to 60 mm CL indicated a lag of two years, with inter-annual trends in PSI in Port Campbell positively correlated with recruitment in both Western and Eastern Zones.

Tasmania

The correlations of PSI with recruitment showed a similar north-to-south trend among the four Tasmanian collector sites (Figure 3, Table 4). Flinders Island PSI was very positively correlated with recruitment from fishery sub-region 3 and 4 while Bicheno PSI was positively correlated with recruitment in its two closest subregions of 2 and 3. Recherche Bay showed no correlation with recruitment (using a 3-year lag) suggesting poor predictive power for subsequent recruitment in its surrounding area of subregion 8.

Future biomass estimates

Biomass in the South Australian Northern Zone was projected forward under a range of TACC scenarios for 2012 to 2016, given the strong relationship between puerulus settlement and recruitment for this area (Figure 4). The TACC levels chosen reflect those currently in use as part of the harvest strategy for the fishery (Linnane et al., 2012). Projections indicate that under all constant TACC scenarios, biomass decreased from 2012 to 2016. Under a TACC of 310 tonnes, biomass declined from 2,418 tonnes in 2012 to 1,918 tonnes in 2016, a decrease of 18%. Under the highest TACC scenario of 430 tonnes, biomass decreased by 38% to 1,481 tonnes.

Discussion

Overall, this study showed that with the exception of Tasmania, spatial trends in PSIs are similar across most of south-eastern Australia suggesting that large-scale oceanographic processes are driving settlement in this region, particularly in South Australia and Victoria. Links between wind-driven circulation and recruitment in *J. edwardsii*, include Harris *et al*. (1988) who correlated westerly winds with yearly total harvest in the Tasmanian fishery and McGarvey and Matthews (2001), who suggested that yearly recruitment might be related to mid-winter western wind strength 5−7 years earlier in South Australia. Within South Australia, storm events, in combination with onshore surface drift during the period of settlement, have been identified as possible mechanisms influencing settlement patterns within these fisheries (Linnane *et al*. 2010a). Specifically, Cirano and Middleton (2004) have shown that during the period of peak puerulus settlement from June to August; mean winds in South Australia and Victoria blow from west to east thus driving an eastward Coastal Current. Superimposed on this circulation are near-surface Ekman Currents that are also wind driven. Eckman Currents during winter are directed onshore throughout South Australia and Victoria and are confined to the surface layer, which is typically 50–100 m deep. Presumably, this system is highly suited to the transportation of pelagic larvae to inshore reefs systems. The highly correlated patterns in settlement across South Australia and Victoria observed in this study would suggest that dominant onshore Eckman during winter are influencing settlement trends across both States.

On the east coast of Tasmania, puerulus settlement is influenced by the position of the sub-tropical convergence, where the Eastern Australian Current meets the cooler Southern Ocean water (Pecl *et al*. 2009), but a direct relation between settlement and current strength has yet to be identified. Bruce *et al*. (2007) highlighted that eastern Tasmania does not have a strong annual cycle in downwelling-favourable wind stress which may explain the lower seasonal signal in puerulus settlement on that coast compared to the South Australian coast. The authors concluded that there was no simple relationship between wind strength and direction and that wind effects were unlikely to be the primary cause of observed seasonal and interannual differences in settlement variability.

Clearly, the ability to predict future fishery recruitment based on annual settlement indices is an advantageous tool, particularly in relation to fisheries management. Overall, this study showed positive correlations between the two variables in each of the major fisheries across south-eastern Australia. In the Northern Zone of South Australia, the period of fours years to recruitment to the MLS of 105 mm CL is consistent with known growth rates in this region (McGarvey *et al*. 1999). Within Victoria and Tasmania the period from settlement to recruitment at 60 mm CL was two and three years respectively. Based on known growth rates of juveniles in these fisheries (Linnane *et al*. 2012), it is estimated that the period from 60 mm CL to legal size (110 and 105 mm CL for males and females respectively) is another 2−3 years suggesting that the total time from settlement to the fishery ranges from four to six years in these regions.

Notably, the relationship failed in two regions, i.e. the Southern Zone region of South Australia where the relationship only appeared correlated in recent seasons and the southern Tasmanian site of Recherche Bay. A range of factors with the ability to distort correlations has been identified in crustacean fisheries. On a large scale, variability is related to distance between the settlement site and the puerulus source (Booth and Phillips 1994). On a finer scale, variability can be influenced by local hydrological and oceanographic conditions such as exposure to currents, position of collectors in relation to open sea and the amount of natural habitat competing with collectors (Butler *et al*. 1995).

In relation to oceanographic conditions, the Southern Zone fishery is the location of an annual coldwater upwelling event known locally as the “Bonney upwelling” while the geographical location of Recherche Bay in southern Tasmania means this region also experiences cooler water temperatures. As a result, growth rates in both these fisheries are some of the lowest in south-eastern Australia (McGarvey *et al*. 1999; Punt *et al*. 1997). Other distortions to the relationship include variations in local growth rates due to density dependence (Booth *et al*. 2001) initial levels of larval production, length of larval life, abundance of predators (Booth 1994; Booth *et al*. 2000) and the absence of a relationship between catches on collectors and settlement on surrounding habitat (Butler and Herrnkind 1991; Butler *et al*. 1995).

Utilising the relationship between puerulus settlement and recruitment to forecast future exploitable biomass is an innovative breakthrough for the future management of lobster resources. Previous comparisons between puerulus catches and changes in the stock were based on catch rate data (Gardner *et al*. 2001); however, since then considerable stock rebuilding has occurred in many of the sampling sites (Linnane *et al*. 2010b). As a result, catch rates in all fisheries are now strongly influenced by the dynamics of the fleet (Linnane and Crosthwaite 2009) and the population dynamics of fully recruited cohorts, rather than year-to-year variation in recruitment. Model estimates take account of stock rebuilding and provide a clearer index of annual changes in the number of recruiting lobsters, while still utilising commercial catch and effort data.

Overall, the results indicate that puerulus monitoring is a relatively robust indicator of future fishery performance and should therefore be regarded as an important management tool for rock lobster resources within south-eastern Australia.

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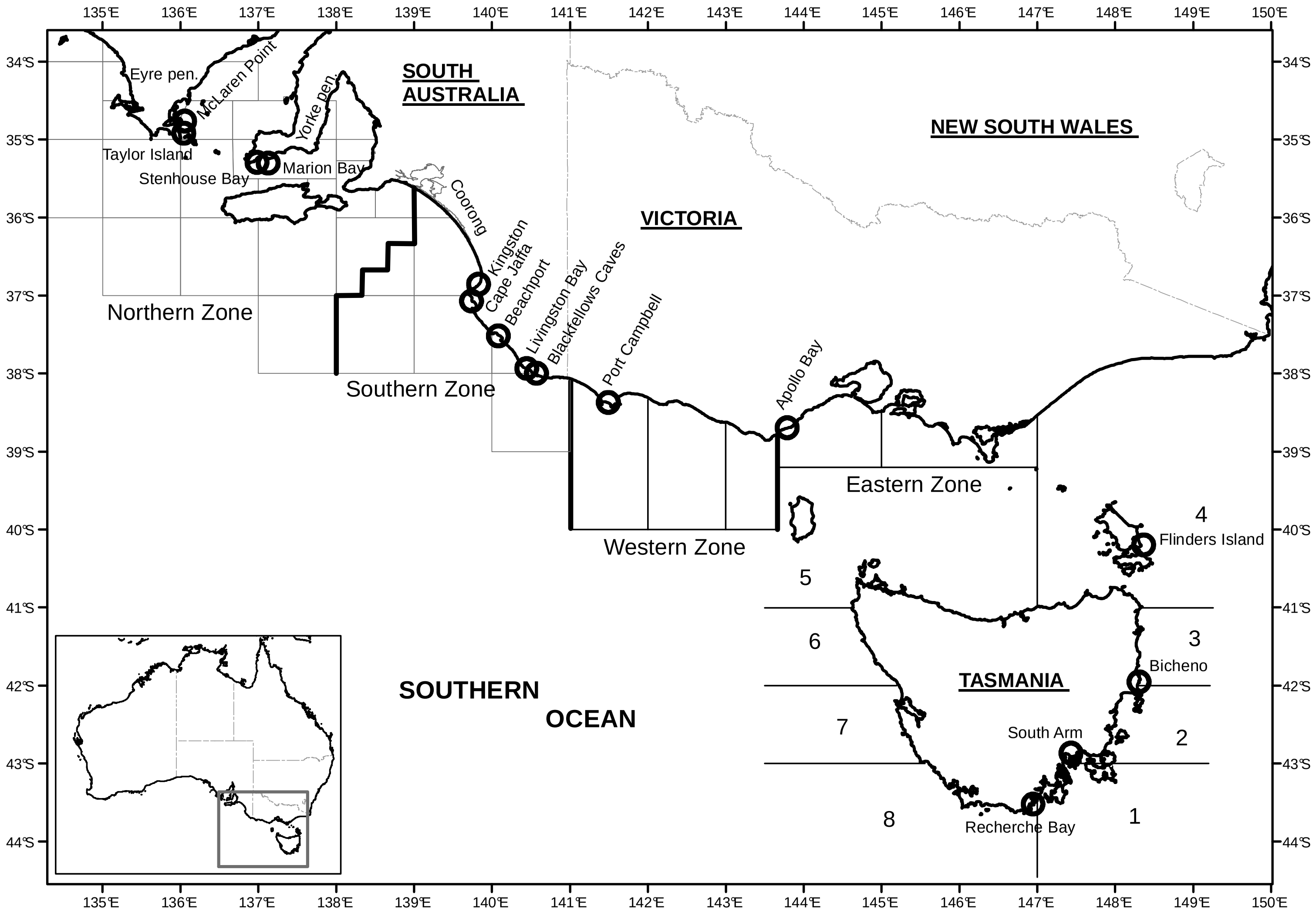

Figure 1. Location of puerulus monitoring sites across South Australia, Victoria and Tasmania

Numbers areas around Tasmania reflect management sub-regions.

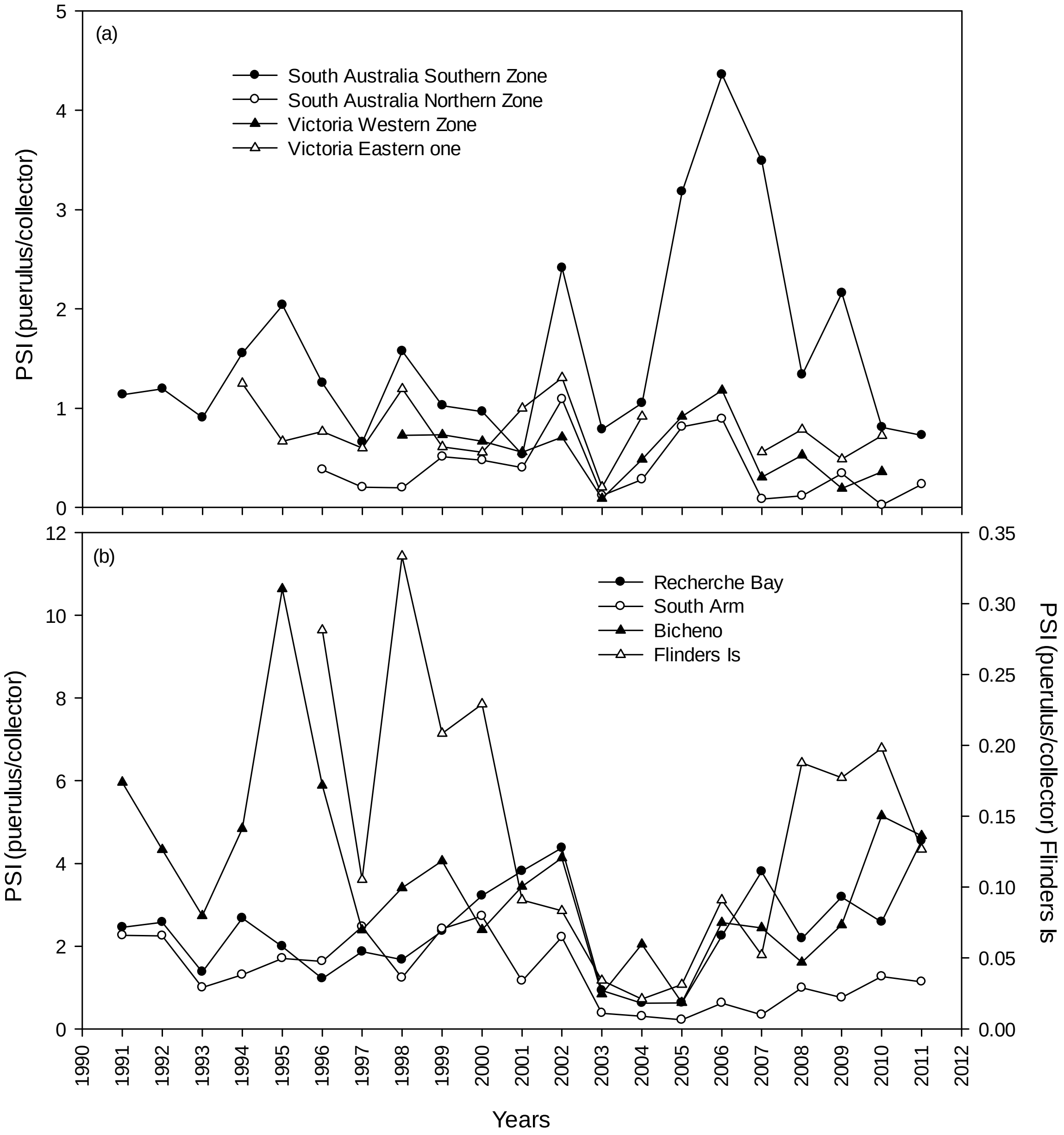

Figure 2. Trends in puerulus settlement index (PSI) in South Australia, Victoria (a) and Tasmania (b).

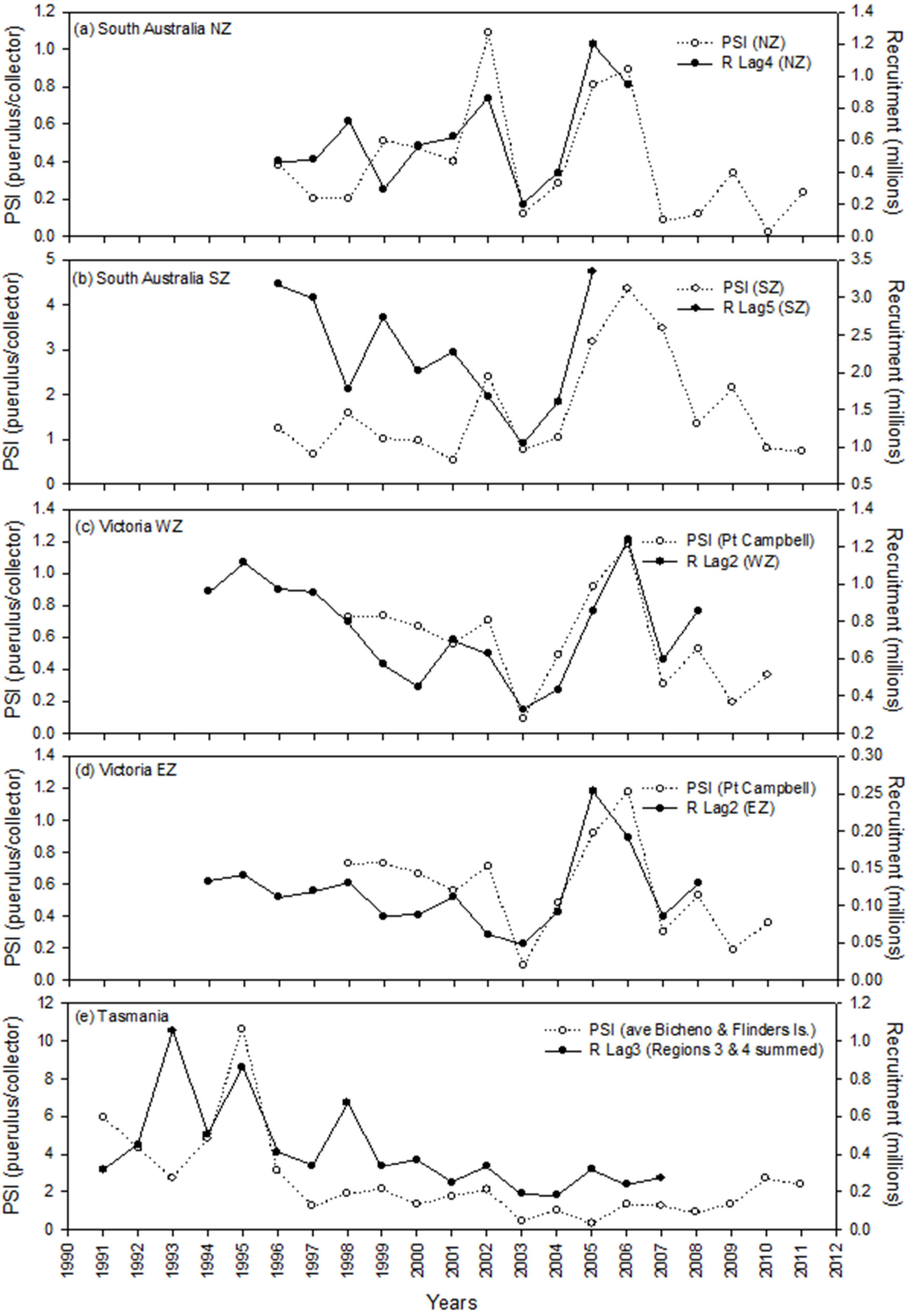

Figure 3. Correlations between puerulus settlement indices (PSI) and lagged model estimated recruitment (R) across South Australia, Victoria and Tasmania.

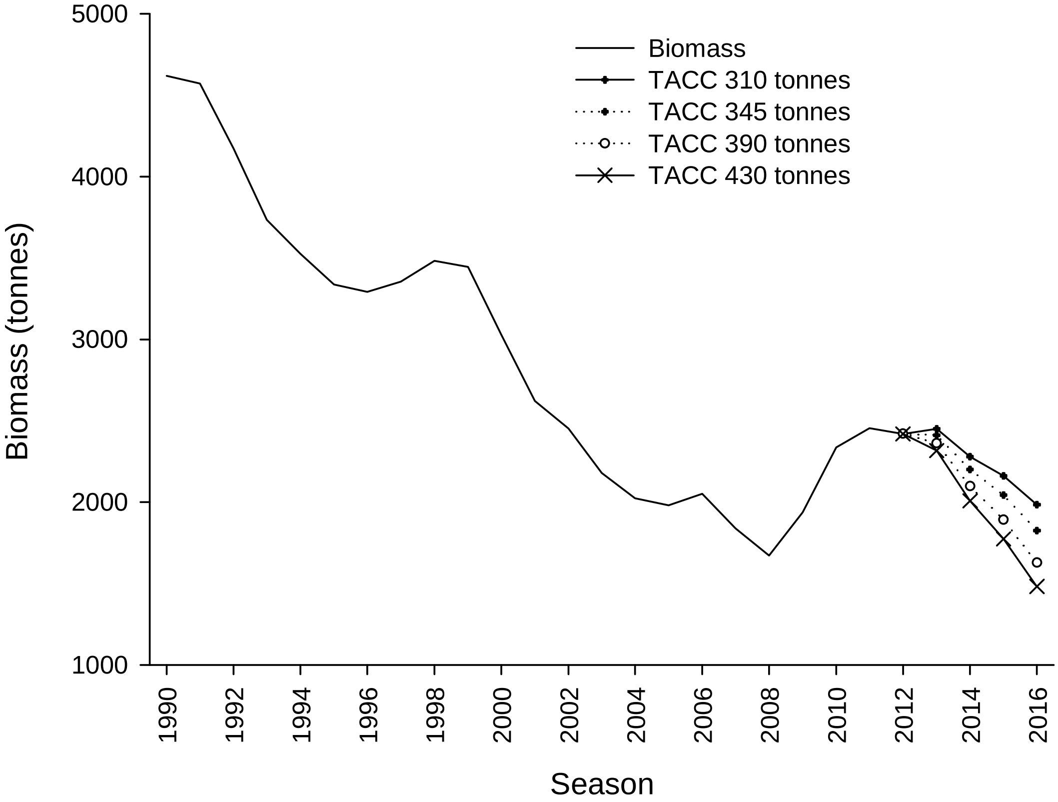

Figure 4. Historical estimates of biomass in the South Australian Northern Zone rock lobster fishery and forwards projections of biomass based on four total allowable commercial catch (TACC) scenarios.

Table 1. Correlations between PSIs across all states

The years of PSI data available varies between fishing regions, therefore correlations were undertaken on all available overlapping years and sample sizes provided. Results in bold are significant at * P <0.05, ** P<0.01.

	TAS Recherche Bay	TAS South Arm	TAS Bicheno	TAS Flinders Is	SA SZ	SA NZ	VIC Pt Campbell	VIC Apollo Bay
TAS − Recherche Bay	1							
TAS − South Arm	0.291 (P=0.100) n=21	1						
TAS − Bicheno	0.186 (P=0.210) n=21	**0.426** **(P=0.027*)** **n=21**	1					
TAS − Flinders Is	0.025 (P=0.464) n=16	**0.488** **(P=0.028*)** **n=16**	**0.541** **(P=0.015*)** **n=16**	1				
SA − SZ	0.044 (P=0.425) n=21	−0.398	−0.114	−0.284	1			
SA − NZ	0.112 (P=0.339) n=16	0.178 (P=0.255) n=16	−0.017	−0.213	**0.533** **(P=0.017*)** **n=16**	1		
VIC − Pt Campbell	−0.075	0.219 (P=0.236) n=13	0.067 (P=0.413) n=13	0.092 (P=0.383) n=13	**0.483** **(P=0.047*)** **n=13**	**0.723** **(P=0.003**)** **n=13**	1	
VIC − Apollo Bay	0.255 (P=0.179) n=15	0.124 (P=0.330) n=15	0.215 (P=0.221) n=15	0.195 (P=0.262) n=13	0.107 (P=0.353) n=15	**0.501** **(P=0.041*)** **n=13**	**0.705** **(P=0.008**)** **n=11**	1

Table 2. Correlations between puerulus settlement index (PSI) and recruitment to minimum legal size in South Australia

Strongest correlations were observed using 4 and 5 year time lags in the Northern and Southern zones respectively. Results show overlapping time series from 1996−2006 (see Figure 2) with actual recruitment years from 2000−2010 in Northern Zone and from 1996−2005 with actual recruitment years 2001−2010 in Southern Zone. Correlations between zones used all overlapping years of data. Results in bold are significant at * P <0.05, ** P<0.001.

	PSI SZ	Recruitment (Lag5) SZ	PSI NZ	Recruitment (Lag4) NZ
PSI – SZ	1			
R (Lag5) − SZ	0.256 (P=0.238) n=10	1		
PSI – NZ	**0.533** **(P=0.017*)** n=16	0.210 (P=0.281) n=10	1	
R (Lag4) – NZ	**0.800** **(P=0.002**)** n=11	0.355 (P=0.157) n=10	**0.733** **(P=0.005**)** n=11	1

Table 3. Correlations between puerulus settlement index (PSI) and recruitment to 60 mm carapace length in Victoria

Strongest correlations were observed using a 2 year time lag in both Western and Eastern Zones. Results show overlapping time series from PSI from 1998−2008 (see Figure 2) with lagged actual recruitment years from 2000−2010. Correlations between sites used all overlapping years of data. Results in bold are significant at ** P<0.01.

	PSI Pt Campbell	PSI Apollo Bay	Recruitment (Lag2) WZ
PSI – Pt Campbell	1		
PSI – Apollo Bay	**0.705** **(P=0.008**)** n=11	1	
Recruitment (Lag2) − WZ	**0.783** **(P=0.002**)** n=11	0.321 (P=0.143) n=13	1
Recruitment (Lag2) − EZ	**0.707** **(P=0.008**)** n=11	0.349 (P=0.121) n=13	**0.674** **(P=0.003**)** n=15

Table 4. Correlations between puerulus settlement index (PSI) and recruitment to 60 mm carapace length in Tasmania

Strongest correlations were observed using a 3 year time lag in settlement from Bicheno and Flinders Island compared with recruitment in Region 3 and 4. Results show overlapping time series from PSI from 1991−2007 (see Figure 2) with lagged actual recruitment years from 1994−2010. Correlations between sites used all overlapping years of data. Results in bold are significant at * P <0.05, ** P<0.001.*

	PSI Recherche	PSI South Arm	PSI Bicheno	PSI Flinders Is
Recruitment (Lag 3) Region 1	−0.189	0.386 (P=0.063)	-0.004	0.133 (P=0.341)
Recruitment (Lag 3) Region 2	−0.243	0.287 (P=0.132)	**0.439** **(P=0.039*)**	0.096 (P=0.384)
Recruitment (Lag 3) Region 3	−0.025	0.260 (P=0.157)	**0.608** **(P=0.005**)**	**0.896** **(P=0.00004***)**
Recruitment (Lag 3) Region 4	−0.174	0.051 (P=0.424)	0.333 (P=0.096)	**0.761** **(P=0.002**)**
Recruitment (Lag 3) Region 8	−0.342	0.030 (P=0.455)	**0.501** **(P=0.020*)**	0.273 (P=0.196)

Spatial and temporal variation in growth of tagged southern rock lobster (*Jasus edwardsii*) in the Victorian fishery

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Abstract

Tag release-recapture data for *Jasus edwardsii* pooled variously into samples at several alternative spatial and temporal resolutions were analysed with stochastic models expressing variation in growth among individuals in a population through the random von Bertalanffy–Fabens parameter k represented by the best of the three positively distributed probability density functions gamma, Weibull and log-normal. Predicted annual length-increment of animals of any specific initial carapace length exhibited a range of probability density curves characterised by three basic shapes. Male samples were mostly ‘central-dome’ shaped (mean near middle), whereas female samples were mostly ‘exponential-decline’ shaped (high proportion of population exhibiting nil or negligible annual length-increment), but some female samples were ‘central-dome’ shaped or ‘left-dome’ shaped. Excepting inadequate sample size, general trends in mean annual length-increment increased from the late 1970s, through late 1990s, to 2000s, and increased approximately from west to east off Victoria. During 2000s, differences in mean annual length-increment for selected sizes were large among 13 separate sites, but small among six separate fishing years at one of these sites, suggesting the long-term trend detected could be explained by differences in the spatial distribution of the tag releases for the three periods rather than by a progressive increase in growth rate over time. Sensitivity testing indicated a need to develop stochastic models that account explicitly for the stepped discontinuous moult-increment growth of crustaceans to improve on models based on the usual assumption of continuous growth.

Introduction

Stock assessment of many of the world’s most valuable fisheries cannot be undertaken applying age-based stock assessment models because the harvested species cannot be readily aged. For these species, it is necessary to apply length-based stock assessment models, which depend on determining growth-transition matrices as undertaken successfully for species of lobsters (Punt *et al.* 2006), prawns (Braccini *et al.* 2013; Punt *et al.* 2009; Wang *et al.* 1995), crabs (McCaughran and Powell 1977), molluscs (Sainsbury 1980; Troynikov *et al.* 1998), and other invertebrate species.

In the Victorian fishery for southern rock lobsters (*Jasus edwardsii*) (SRL), a statutory obligation requires on-going stock assessment to set annually a Total Allowable Commercial Catch (TACC) for each of Western Zone (WZ) and Eastern Zone (EZ) (Figure 1) (Anonymous 2009). The TACC is estimated using a purpose-built rock lobster fishery stock assessment model designed for assessment of the SRL fisheries in Victoria, South Australia, and Tasmania and developed over the past 15 years (Hobday and Punt 2001; Hobday and Punt 2009; Hobday *et al.* 2005; Linnane and Crosthwaite 2009; Punt and Kennedy 1997; Punt *et al.* 2013). This size-structured population dynamics model, for each sex separately, represents growth with a matrix specifying the probability of a SRL growing from one size-class to each of a range of other possible size-classes in a specific time step. For the past decade, up to and including 2011, an early version of the model was applied each year in Victoria to each zone in annual time-steps applying a single growth-transition matrix that ignored any differences in the growth of SRLs among separate localities across the zone and among separate periods. For the 2013 stock assessment (Walker *et al.* 2013), the latest version of the model was operated with 5-mm size-classes (starting size 60 mm carapace length) with updated growth-transition matrices from the present study. Growth, and hence recruitment, was applied at the end of October, immediately prior to the beginning of each fishing year (1 November to 31 October).

An earlier study of the growth of *J. edwardsii* in the Victorian rock lobster fishery (Punt *et al.* 2006) found spatial differences in length-increment growth among separate regions across the range of the fishery and detected temporal differences using tag release-recapture data for the period 1975–2005. The present study follows up on this earlier study in the Victorian fishery by further exploring spatial and temporal variation in length-increment growth with the advantage of the availability of an additional 7 years of tag length-increment growth data. Initially, the present study compares annual length-increment between WZ and EZ for males and females separately with all sources of tag length-increment growth data pooled for the 36-year period from

1975–76 to 2010–11 fishing years. The study then tests for differences among three periods referred to as Late 1970s, Late 1990s, and Most 2000s within each of six regions (same as earlier study) across Victoria (Figure 1) where there were sufficient data. The study then compares SRL annual length-increment among 13 specific sites (data from a 14th site were pooled with one of the 13 sites) from annual fixed-site survey (from 1995–96 to 2010–11 fishing years in EZ and from 2001–02 to 2010–11 fishing years in WZ) (Figure 2). Finally, the study compares SRL annual length-increment among six separate fishing years from 2001–02 to 2006–07 for one particular site from annual fixed-site survey with particularly large sample size.

Methods

Data collection

Southern rock lobsters cannot be readily aged, so their growth was investigated using tag release-recapture length-increment growth data. SRLs were tagged by inserting serially numbered tags ventrally in the first abdominal segment, and were sexed and measured for carapace length, l_C, at tag release and tag recapture. Measured to the nearest millimetre, l_C is the dorsal measurement from between the basal plates of the antennae to the posterior edge of the carapace. Tagging of SRLs in Victoria began during the 1975–76 fishing year and small numbers were tagged throughout the waters off Victoria over a 7-year period to the end of the 1981–02 fishing year. SRLs were not tagged routinely until the 1995–96 fishing year, 2 years after adoption of annual fixed-site survey aboard chartered commercial vessels during 1993–94 in EZ (initially 5 sites reduced to 2 sites) and during 2001–02 in WZ (13 sites treated as 12 sites by pooling sites NM and BR) (Table 1; Figure 2). In addition, SRLs were tagged routinely as part of on-board scientific observation across the fishery initiated during 2004–05. Most tag and release was undertaken by trained observers on commercial vessels, but some were tagged by several commercial fishers on a voluntary basis and by scientific divers.

Data associated with recapture of tagged SRLs were variously reported by commercial fishers, trained observers, in-port samplers, recreational divers, and fisheries compliance officers who were not all able to provide, or were not aware of, the recapture information required. For example, it was unusual for in-port samplers to have access to position of recapture of SRLs or for recreational divers to have appropriate callipers, as issued to commercial fishers licensed in the fishery, for accurately measuring l_C of SRLs. Procedures for handling and tagging of SRLs have been consistent for all periods in Victoria.

Data selection

Several types of uncertainty in the tag-release-recapture data were identified and records were rejected for several reasons from the data used for analyses in the present study. The uncertainties included incorrect tag number (tag recapture reported for tag identification number with no record of tag release), different sex of SRL reported between tag release and tag recapture, missing length-increment, and negative length-increment in l_C between date of tag release and date of tag recapture raising questions of whether this was caused by negative growth, measuring error, or gross error. Where a record with negative length-increment was accepted (–1 or –2 mm), length-increment was set to zero for the purpose of data analysis on the assumption that negative growth does not occur. Most errors in records for recaptured tagged SRLs were identified during entry and subsequent editing of data, and were appropriately coded to enable subsequent identification in the database for the purpose of providing the option for rejection or acceptance of records depending on the type of data analysis. Where a tagged SRL was recaptured and reported several times (up to five times in the data), only data from the final recapture, were used in the data analyses for the present study, because tagged SRLs at liberty for the longest period are the most informative.

The computer statistical package SAS (version 9.1) (SAS Institute, Cary, North Carolina, USA) was used for entry, management, summary, and preliminary analysis of the data. Information associated with tag release and tag recapture were stored separately in SAS tag database files, which were merged for calculating length-increment growth, time-at-liberty, and distance travelled and for identifying erroneous data.

Growth model and adjustment for SRL length-selectivity

A method for modelling the growth of SRLs was adopted that assumes all animals in the population grow differently and that individual variation in growth can be expressed through the random von Bertalanffy–Fabens parameter k represented alternatively by three positively distributed probability density functions (pdf) (Troynikov 1998). The parameter ℓ_∞ in this stochastic model represents the limit on maximum size expected in the population, unlike in deterministic models where the parameter is the predicted average maximum size. When estimating these growth parameters, the method adjusts for SRL length selectivity of lobster pots on the probability of recapturing a tagged animal (Troynikov 1999; Troynikov and Walker 1999), depending on whether (Treble 1996; Treble *et al.* 1998; Walker 1977) or not the pots were fitted with escape-gaps.

The performance of the models in fitting the data was discriminated by using the approximation to Kullback's information mean or information integral to avoid invalid assumptions about the distributions of growth parameters and eliminate the worst two models from the set of three models derived from alternative pdfs (Troynikov and Walker 1999). For comparing growth parameters between different stochastic models, the values of mathematical expectation $E[k]$ and standard deviation $SD[k]$ were recalculated from the maximum likelihood estimates of the parameters of gamma, Weibull and log-normal pdf; i.e. $E[k]$ and $SD[k]$ are not estimated directly. The relationships between these parameters and values of $E[k]$ and $SD[k]$ are not linear; hence, standard errors for $E[k]$ and $SD[k]$ are not available.

Commercial lobster pots are of mesh construction and have escape-gaps fitted (legislated for start of 1990−91 fishing year), which together are designed to reduce retention of SRLs of size below the legal minimum length (LML) of 110 mm for males and 105 mm for females. The length-selection characteristics of the various lobster pot configurations for tag recapture create potential biases in the growth parameter estimates and require adjustment depending on the specific configuration relating to construction of the lobster pots and the presence or absence of escape-gaps.

In Victoria, two experiments tested the effects of escape-gaps on retention of SRLs in the lobster pots. The first experiment (Walker 1977) (referred to as Portland Escape-gap Experiment) was designed to test the effects of three factors on retention of SRLs of size below LML and of size above LML. These factors were escape-gap size (vertical dimension of slot), escape-gap elevation (distance from floor of pot to bottom of slot), and position of buoy line attachment at the top of the pot (same side as escape-gap or opposite side from escape-gap). The experiment, designed to determine the optimum combination of factors, indicated that escape-gap size and escape-gap elevation (6 escape-gap sizes x 7 escape-gap elevations x 2 escape-gap sides = 84 escape-gap combinations), but not escape-gap side, had significant effects on retention of SRLs. On the basis of this experiment, it became mandatory during 1990–91 for an escape-gap of escape-gap size of 60 mm (and >250 mm wide) to be fitted to each commercial lobster pot. The second experiment (Treble 1996) (referred to as Apollo Bay Escape-gap Experiment) was designed specifically to determine the selectivity of a pot fitted with an escape-gap of 60-mm size as a function of carapace length of SRL. Analyses fitting size-selectivity curves to data from the Portland Escape-gap Experiment using the asymmetric Richards function and to data from the Apollo Bay Escape-gap Experiment using separately the symmetric logistic function and the asymmetric Richards function indicated that the Richards function fitted to the data from the Apollo Bay Escape-gap Experiment data best (Treble *et al.* 1998). The size-selectivity curve determined from the Portland Escape-gap Experiment was not used as part of standard analysis in the present study because the multiple escape-gap elevations are likely to have biased the selectivity curves; rate of retention of SRLs varied markedly with escape-gap elevation. Hence, for the present study, apart from sensitivity testing for effect of selectivity function, only the selectivity curve determined from fitting to data from the Apollo Bay Escape-gap Experiment based on the Richards function with the parameter p ('relative fishing intensity' of the experimental and control fishing gear in the experiment as defined by Treble *et al.* 1998) set to 0.65 was used for adjusting for the effects of SRL length selectivity of lobster pots on the probability of recapturing a tagged animal.

The various lobster pot configurations capturing SRLs for tag release or tag recapture in Victoria include standard commercial pots fitted without escape-gaps (WZ and EZ prior to 1990−91 fishing year), standard commercial pots fitted with escape-gaps open (normal commercial fishing), standard commercial pots fitted with escape-gaps closed (WZ during fixed-site survey), research pots constructed without escape-gaps (WZ), and research pots constructed of double fine-mesh covering without escape-gaps (EZ). For each recaptured tagged SRL reported with the required recapture details, it was assumed that the distance travelled between the position of tag release and the position of tag recapture was sufficiently small for the length-increment growth of the SRL to be representative of growth at the position of release. For analyses of growth by site, only tag releases from fixed-site survey were used, whereas for analyses of growth by zone or region, all sources of tag release were used.

Data analysis

Variation in growth of SRLs of males and females separately was explored through five sets of analyses comparing differences in length-increment among various spatial and temporal selections of data. These analyses are referred to as 'inter-zone comparison', 'inter-region comparison', 'inter-period within region comparison', 'inter-site comparison', and 'inter-annual within one-site comparison'. Comparison of variation in annual length-increment among two or more samples of tag release-recapture data was based on mean, median and a selected probability interval (PI) from the probability density curve (pdc) in annual length-increment, which were used for graphical representation of one or more of the three initial SRL carapace lengths of 60 mm, 80 mm and 100 mm. The appropriate pdc for each sample was determined from the pdf for the distribution of k best-fitting the data from among the three pdfs of gamma, Weibull and log-normal by Kullback's information mean. The model-parameter estimates for ℓ_∞, $E[k]$, and $SD[k]$ are presented, but little attention is given to their values, because, as with all growth analyses, their values are inevitably correlated and each has little intrinsic meaning on its own.

Pooled data over all years for male and female SRLs separately in each of WZ and EZ were used to undertake two initial sensitivity tests with the stochastic growth models. The first test explored sensitivity to correction for length-selective bias using the Richards selectivity function from the Portland Escape-gap Experiment and using the Richards function from the Apollo Bay Escape-gap Experiment; i.e. the two combinations of Portland–Richards and Apollo Bay–Richards. The second test was designed to determine whether varying minimum period, T, of tagged SRLs at liberty (from T=0.25 years, through 0.50 and 1.00, to T=2.00 years) for data selection affected the results. For comparing differences in length-increment among the five sets of spatial and temporal selections of data, a standard of T=0.50 years was adopted (see Discussion for justification).

The first set of analyses ('inter-zone comparison') was designed to compare length-increment growth between the two zones, where data were pooled from all sources within each zone over all years for which tag-recapture data were available. The second set of analyses ('inter-region comparison') was designed to compare length-increment growth among the six regions, where data were pooled from all sources within each region over all years for which tag-recapture data were available. The third set of analyses ('inter-period within region comparison') was designed to compare length-increment growth among three periods within each of the six separate regions, where data from all sources were pooled within each region. The three periods were selected on the basis of data availability in each region and separation from other periods: from 1975–76 to 1978–79 fishing years (referred to herein as Late 1970s), from 1994–95 to 1998–99 (Late 1990s), and from 2002–03 to 2010–11 (Most 2000s). The fourth set of analyses ('inter-site comparison') was designed to compare length-increment growth among the sites adopted for annual fixed-site survey, where data were pooled for each site over years for which tag-recapture data were available (from 2001–02 to 2010–11 fishing years for 12 sites in WZ and from 1995–96 to 2010–11 fishing years for 2 sites in EZ). These 14 sites were from the four western-most regions off Victoria (Figure 2). The fifth set of analyses ('inter-annual within one-site comparison') was designed to compare length-increment growth among fishing years within a single site from annual fixed-site survey. This selected site DBE (Discovery Bay East) had particularly large sample sizes each year during the 6-year period from 2001–02 to 2006–07 fishing years.

Results

Summary of tag release–recapture data

The history of collection of tag release-recapture data in Victoria can be divided into the 7-year period from 1975–76 to 1981–82 fishing years and the 18-year period from 1993–94 to 2010–11 fishing years. The first period can be characterised by a small number of tag releases as a result of special projects, whereas the second period can be characterised by on-going routine tag releases involving large numbers of SRLs. During the first (7-year) period, 8982 SRLs were tagged and released off Victoria (6438 in WZ and 2544 EZ) of which 1812 (20.2%) were recaptured and reported with data adequate for growth analysis, where data for multiple recapture and release are excluded. During the second (18-year) period, 70,305 SRLs were tagged and released off Victoria to the end of the 2010–11 fishing year of which 8065 (10.7%) were recaptured and reported with adequate data by the end of the period (Table 2). Of the SRLs tagged and released, 48,002 SRLs were tagged as part of annual fixed-site survey (42,037 in WZ and 5965 in EZ) and 22,303 were tagged as part of scientific on-board observation (including a small number tagged by commercial fishers on voluntary basis and by divers) (18,256 SRLs in WZ and 4047 SRLs in EZ). Of the tagged SRLs recaptured and reported with adequate data, 5101 (9.7%) were tagged as part of annual fixed-site survey (4531in WZ and 570 in EZ) and 2964 were tagged as part of the scientific on-board observation (2391 in WZ and 573 in EZ).

Summaries of the number of tag recaptures for each fishing year by sex and region separated by data source (Table 3.1) and data source pooled (Table 3.2) indicate a total of 9877 tag recaptures with adequate data for the 36-year period from 1975–76 to 2010–11. Large sample sizes of recaptures from fixed-site survey during the period from 2001–02 to 2010–11 fishing years in WZ and from 1994–95 to 2010–11 in EZ (Table 3.1) provide sufficient data for statistically robust 'inter-site comparison' and 'inter-fishing-year within site comparison' of annual length-increment growth. Of the total of 9877 tag recaptures, 8468 (85.7%) were included in the 'inter-period within region comparison' where the number of tag recaptures decreased from west to east: Portland Region (41.9% of number recaptured), Warrnambool Region (28.4%), Apollo Bay Region (16.0%), Queenscliff Region (11.5%), San Remo Region (0.6%), and Lakes Entrance Region (1.6%). For these same included recaptures, the selected periods increased with time: Late 1970s (19.8%), Late 1990s (27.8%), and Most 2000s

(52.4%). Tag-release-recapture data pooled from all years within region and within zone were used for 'inter-region comparison' and 'inter-zone comparison', respectively.

The length-frequency distributions of all recaptured tagged SRLs shown for both release length and recapture length in each zone (Figure 3) indicate that most males were of carapace length less than the LML (l_C of 110 mm for male LML) when tagged and released), whereas many of the females were of carapace length greater than the LML (l_C of 105 mm for female LML). Scientific observers were able to tag female SRLs of $l_C \geq$LML during May–September when the season was open for males, but closed for females. Number of tag releases increased progressively with l_C from 80 mm to LML, with a very small number tagged in the range 60–79 mm. Although for many of the tag recaptures $l_C <$LML, most had $l_C \geq$LML.

Spatial and temporal comparison of annual length-increment

The annual length-increment pdcs exhibited three patterns referred to herein as 'central-dome' shape, 'left-dome' shape, and 'exponential-decline' shape. These names are adopted for convenience and convey approximate description of the shapes. 'Central-dome' shape implies low frequency for small length-increment, higher frequency for intermediate length-increment, and low frequency for large length-increment) (average near middle). 'Exponential-decline' shape implies a high proportion of population exhibiting nil or negligible annual length-increment and frequency reducing with increasing length-increment (the shape does not follow an exponential function). 'Left-dome' shape (average between zero and middle length-increment and falls between the 'central-dome' and 'exponential-decline' shapes. Through these three shapes from 'central-dome' shape to 'exponential-decline' shape was a trend from very weak right skew to strong right skew with a tail, where pdcs with long tails were progressively less well defined with increasing annual length-increment. For most graphical representations, the 90% PI from 5% to 95% of the pdc is presented for these patterns, except where the asymptotic tail associated with strong right skew such that more than 5% of the upper part of the pdc approached or exceeded 50-mm length-increment, then the 85% PI (with 90% upper limit) or narrower PI (with <90% upper limit) for the pdc is presented. Estimates for the parameters ℓ_∞, $E[k]$, and $SD[k]$ from the best of the three tested pdfs from each analysis are tabulated, which are of less biological significance (see Discussion) than the shapes of the pdcs and the magnitudes of the mean, median and PI in annual length-increment for each of the three initial SRL carapace lengths of 60 mm, 80 mm and 100 mm.

Inter-zone comparison with sensitivity analyses

Pooling all available tag release-recapture length-increment data remaining after applying the data selection criterion of minimum time at liberty of T=0.50 years across all sites and regions for the entire 36-year period from 1975–76 to 2010–11 fishing years provided data for 2724 males and 4216 females from WZ, and 398 males and 637 females from EZ (Table 4.1.1). Applying the Richards selectivity function determined from the Apollo Bay Escape-gap Experiment for adjustment of effects of SRL length selectivity of lobster pots, variation in annual length-increment for each of the males in WZ and females in WZ and EZ was best represented by the pdc derived from the model with the gamma pdf for the distribution of k, whereas for males in EZ, it was best represented by the pdc derived from the model with the Weibull pdf for the distribution of k. The shapes of the annual length-increment pdcs were very similar between the two zones for each sex, but the shapes were very different between the males and females (Figure 4.1.1). The males exhibited 'central-dome' shaped pdcs, whereas the females exhibited 'exponential-decline' shaped pdcs. The important implication of these pdc shapes is that a large proportion of the female population exhibited little or no growth, whereas only a very small proportion of the male population exhibited little or no growth. The 90% PI from 5% to 95% of each pdc is presented for males, but for females, because the long asymptotic tails associated with right skew, the 85% PI from 5% to 90% of each pdc is presented. Mean annual length-increment was 2 mm higher in WZ than EZ at initial sizes of 60 mm, 80 mm, and 100 mm carapace length for both males and females, with the one exception of 3 mm higher at 60 mm for females (Table 4.1.1). The exact same data or subsets of the data were applied to test the effects of choice of selectivity function for correction for effects SRL length selectivity of lobster pots and choice of T, although increasing T from 0.50 to 1.00 or 2.00 years reduced sample size and decreasing T from 0.50 to 0.25 years increased sample size for growth analysis.

Choice of selectivity function—Richards function determined from the Apollo Bay Escape-gap Experiment or Richards function determined from the Portland Escape-gap Experiment—affected selection of the most representative pdf for the distribution of k and values of estimates for parameters ℓ_∞, $E[k]$, and $SD[k]$ (Table 4.1.1). However, the choice of selectivity function had little effect on the pdcs (Figure 4.1.2) and mean annual length-increment (maximum difference of only 0 or 1 mm for any of the SRL initial lengths of 60 mm, 80 mm, and 100 mm for each of males and females) (Table 4.1.1). For selectivity adjustment, when changing from the

Richards selectivity function determined from Apollo Bay Escape-gap Experiment to the Richards selectivity function determined from Portland Escape-gap Experiment, the pdcs were similar except at low values of length-increment for females in both WZ and EZ.

In both WZ and EZ, the effect of altering T on pdc shape was larger than the effect of changing the selectivity function for selectivity adjustment. With the selectivity function standardised as the Richards selectivity function determined from Apollo Bay Escape-gap Experiment, increasing T from T=0.25 years, through 0.50 and 1.00 to T=2.00 years altered the pdc from 'left-dome' shape to progressively more 'central-dome' shape for males and from 'exponential-decline' shape to progressively less-strong left-dome shape for females (Figure 4.1.3). For males, as pdc became more symmetrical with increasing T, the 90% PI narrowed with little effect on mean annual length-increment for either WZ and EZ. For females, the effects of increasing T were consistent with the male pattern of narrowing PI, but the 90% PI could be drawn only for T=2.00 years (WZ and EZ) and for T=1.00 years (EZ only), otherwise only 80% and 85% PIs could be drawn, except for T=0.25 years in EZ, which PI could not be drawn at all (Figure 4.1.4).

Inter-region comparison

The 'inter-region comparison' was based on dividing the data adopted for the 'inter-zone comparison' into the six regions for the entire 36-year period from 1975−76 to 2010−11 fishing years. Sample sizes were high for Portland Region (1331 males, 1911 females) and Warrnambool Region (961, 1505) and moderate for Apollo Bay Region (432, 800) and Queenscliff Region (305, 414), but low for San Remo Region (8, 43) and Lakes Entrance Region (85, 193) (Table 4.1.1). These sample sizes indicate that growth was better determined in the western regions of Victoria, where commercial catches were highest, than in the eastern regions.

As with the 'inter-zone comparison', the patterns of annual length-increment pdcs among the six regions were very different between the males and females. For males, the pdcs among the six regions were all 'central-dome' shaped and fairly similar, with the exception of San Remo Region which had the narrowest 90% PI and highest mean annual length-increment, but also had a very small sample size (n=8). For females, the pdcs among the regions varied such that some (Queenscliff Region, Portland Region, and Lakes Entrance Region) were 'left-dome' shape and can be shown with 90% PIs, whereas the others exhibited 'exponential-decline' shape with strong-right skew such that more than 5% of the pdc exceeded 50 mm annual length-increment and the results had to be presented with a PI of 85% (5−90%) for Warrnambool Region, 75% (5−80%) for Apollo Bay Region, and 50% (5−55%) for San Remo Region (Figures 4.1.5, 4.1.6). Mean annual length-increment among the regions varied 15−20 mm for males and 5−10 for females.

Inter-period within region comparison

The 'inter-period within region comparison' was based on selecting subsets of data for three periods (Late 1970s, Late 1990s and Most 2000s) from the data selected for the 'inter-region comparison' from the entire 36-year period from 1975−76 to 2010−11 fishing years. Overall sample sizes across the six regions varied among the three periods of Late 1970s (341 males, 782 females), Late 1990s (591, 938), and Most 2000s (1692, 2290) such that sample size increased progressively with time (Table 4.2.1). There were no data during Late 1970s or Most 2000s in San Remo Region or during Most 2000s for Lakes Entrance Region.

As with the 'inter-zone comparison' and 'inter-region comparison', the patterns of annual length-increment pdcs among the three periods within each of the six regions, where data were available, were very different between the males and females. The 15 period-regions with available data from the 18 possible period-regions (i.e. 3 periods x 6 regions) had 30 data sets (15 period-regions x 2 sexes) where nine (two male and seven female) had 'exponential-decline' shape with strong-right-skew-shape pdcs and had to have the PIs truncated from 90% (5−95%) to 85% (5−90%) for seven, to 80% (5−90%) for one female region-period (Warrnambool Region Late 1990s), and to 55% (5−60%) for another female region-period (San Remo Region Late 1990s). For males, the pdcs were all 'central dome' shape with only two exceptions, which had 'exponential-decline' shape for Late 1970s in Portland Region and in Queenscliff Region. For females, the pdcs were of 'central-dome' shape for only Most 2000s in Queenscliff Region, but seven of the 15 period-regions had 'exponential-decline' shape: three during Late 1970s (Apollo Bay Region, Queenscliff Region, and Lakes Entrance Region), three during Late 1990s (Portland Region, Warrnambool Region, and San Remo Region), and one during Most 2000s (Warrnambool Region) (Table 4.2.1). While consistent with the pattern of a large proportion of females exhibiting little or no growth in Warrnambool Region, Apollo Bay Region, and San Remo Region from the 'inter-region comparison', the 'inter-period within region comparison' indicate that males to some degree and females to a much greater degree exhibited little or no growth through 'exponential-decline' shaped pdcs to a greater extent during the early than during the later periods (Figure 4.1.3).

Spatial and temporal trends of variation in mean annual length-increment were evident among the three periods Late 1970s, Late 1990s, and Most 2000s and among the six regions across Victoria from the results of the 'inter-region comparison' and 'inter-period within region comparison'. Exceptions departing from these trends occurred mostly when sample size was small.

The spatial trend, with the exceptions of Warrnambool Region and Lakes Entrance Region, was increasing mean annual length-increment from west to east such that Warrnambool <Lakes Entrance <Portland <Apollo Bay <Queenscliff <San Remo. This pattern occurred for both males and females during all three periods, except Late 1970s in Warrnambool Region for both males (n=10) and females (n=22) and in Lakes Entrance Region for males (n=14), where mean annual length-increment was higher than expected from the trend. For all data pooled across period by region, males conformed to the trend, but females departed from the pattern in Apollo Bay Region (n=800) with a marginally smaller than expected mean annual length-increment and in San Remo Region (n=43) with a much smaller than expected mean annual length-increment (Tables 4.2.1, 4.2.2; Figures 4.1.5, 4.2.1). The lack of conformity for San Remo Region was not unexpected given small sample size and data were available only for Late 1990s.

The temporal trends were different between the males and females (Table 4.2.3; Figure 4.2.1). For females, mean annual length-increment increased from Late 1970s, through Late 1990s, to Most 2000s; the only exception was Late 1970s in Lakes Entrance Region (n=22). For males mean annual length-increment increased from Late 1970s to Late 1990s and then decreased from Late 1990s to Most 2000s, exceptions being during Late 1970s in Warrnambool Region (n=10) and in Lakes Entrance Region (n=14) and during Most 2000s in Queenscliff Region (n=67). However, this trend of increase and then decrease for males is evident for the initial carapace lengths of 60 mm, 80 mm and 100 mm, but at larger sizes of 110 mm and 140 mm, the trend of progressively increasing mean annual length-increment through the three periods is evident for Portland Region, Apollo Bay Region, and Queenscliff Region, but not for Warrnambool Region (Figure 4.2.2).

Inter-site comparison

Of the 12 sites from fixed-site survey in WZ (4 in Portland Region, 5 in Warrnambool Region, and 3 in Apollo Bay Region) for the 10-year period from 2001−02 to 2010−11 fishing years and of the 2 sites in EZ (2 in Queenscliff Region, 0 in San Remo Region, and 0 in Lakes Entrance Region) (Figure 2) for the 16-year period from 1995−96 to 2010−11 fishing years, there were sufficient data to undertake growth analysis and to determine a growth-transition matrix at each of most sites for each sex. One exception created the need to pool the sites NM and BR to provide a sufficiently large sample size to obtain results, which reduced the number of length-increment analyses in Apollo Bay Region from three to two.

Mean annual length-increment is higher for males than for females, but variation in mean annual length-increment among fixed sites was higher for females than for males, particularly in Warrnambool Region (Table 4.3.1; Figure 4.3.1). The trends of mean annual length-increment from lowest to highest were similar for males (DBD <DBE <P <DBW) and females (DBE <DBD <P <DBW) in Portland Region, and the same for males and females in Apollo Bay Region (NM & BR <MH) and in Queenscliff Region (T <OG). In Warrnambool Region, the pattern of the order among the sites was very different between males (WD <PFW <WE <WS <WW) and females (WS <WW <WD <WE <PFW). Differences between minimum and maximum mean annual length-increment among the 13 separate sites were comparatively large for SRLs at 60 mm carapace length (15 mm for males and 16 mm for females), 80 mm (10, 12 mm), and 100 mm (9, 10 mm).

For males, the pdcs for all 13 analyses were 'central-dome' shape, and for females, 11 of the 13 pdcs were mostly 'central-dome' shape (DBW, DBD, P, PFW, T, OG) or 'left-dome' shape (DBE, WW and NM & BR) (Table 4.3.1). However, two of the pdcs in Warrnambool Region were 'exponential-decline' shape (WD and WS), such that a large proportion of the population exhibited zero or negligible length-increment and had to be presented with truncated PIs of 85% (5−90%) (Figure 4.3.1).

Inter-annual within site DBE comparison

The site DBE (Discovery Bay East) was the only site considered to have adequate sample size (n>40) for each of a series of fishing years (six years from 2001−02 to 2006−07) to undertake an inter-annual comparison of growth length-increment for each of males (n=53−105) and females (n=47−148), separately (Table 4.4.1). Differences between minimum and maximum mean annual length-increment among fishing years were comparatively small for SRLs at 60 mm carapace length (5 mm for males and 5 mm for females), 80 mm (3, 3 mm), and 100 mm (1, 1 mm) (Table 4.4.1; Figure 4.4.1). Similarly, the variation in magnitude of 90% PIs was comparatively small among fishing years for SRLs of initial length 60 mm (PI range 24−31 mm for males and 18−32 mm for females), 80 mm (18−23 mm, and 12−21 mm), and 100 mm (12−16 mm, and 6−10 mm) (Figure 4.4.1). The patterns of variation in annual length-increment evident from pdcs among the six fishing years were remarkably similar for each of males ('central dome') and females ('left dome') (Figure 4.4.2). The pattern of change in mean annual length-increment was generally consistent between males and females with a marginal decline from 2001−02 through 2002−03 to 2003−04, and slightly more rapid increase to a maximum in 2004−05, followed by a subsequent decline to a minimum for males during 2006−07, whereas the female minimum was during 2002−03 (Figure 4.4.1).

Growth-transition matrices

For the 2012 Victorian stock assessment (Walker *et al.* 2012), a growth-transition matrix was obtained for each sex in each of Portland Region, Warrnambool Region, Apollo Bay Region, and Queenscliff Region from equally weighting the growth-transition matrices of the sites within each region. Similarly, a growth-transition matrix was obtained for each sex in the WZ from equally weighting the growth-transition matrices of Portland Region, Warrnambool Region, and Apollo Bay Region within the zone. The growth-transition matrix for Queenscliff Region was applied to EZ for application in the stock assessment model. Results from the present study indicate that for the purpose of application of the stock assessment model, it is not only important to have separate growth-transition matrices for the different regions of Victoria, but also for them to be varied over time. Hence, within each of the four regions separately, a growth-transition matrix for each of the males and females was determined for each year between Late 1970s and Late 1990s and between Late 1990s and All 2000s, where the annual matrices vary inter-annually smoothly from one period to the next. These growth-transition matrices varying over time are yet to be tested in the SRL stock assessment model.

The concepts of ℓ_∞ and l_{Max} are equivalent in the model adopted for growth analysis in the present study and application of the growth-transition matrices in the stock assessment model can be problematic when fitting to various sources of length-frequency composition data. Given that the length-frequency data are collected from many more sites than that for tag length-increment growth, it is inevitable that l_{Max} for length-frequency sampling will exceed ℓ_∞ for tag release-recapture at specific sites in particular fishing years. This is demonstrated by the higher proportion of SRLs of $l_C \geq$LML exceeding l_{Max} in length-frequency samples from in-port and scientific onboard observation than from fixed-site survey (Tables 5.1–5.3). In general, the growth-transition matrices determined for the four western-most regions off Victoria from fixed-site survey adequately cover the available fishery-monitoring length-frequency data for the regions. The only exceptions are the growth-transition matrices for males in the Apollo Bay Region (9.3%) and females in the Queenscliff Region (5.6%) (Tables 5.1, 5.2, 5.3) where the number of fixed sites is small.

Discussion

Spatial and temporal variation in growth

Several broad conclusions are drawn from the results of analysis of the 84 tag release-recapture samples for the ‘inter-zone’, ‘inter-region’, ‘inter-period within region’, ‘inter-site’, and ‘inter-annual’ comparisons of the present study. Mean annual length-increment mostly increased from late 1970s, through late 1990s, to 2000s, with the exception of males of size <100 mm decreasing from late 1990s to 2000s. For each of males and females, mean annual length-increment among six broad regions increased from west to east off Victoria, except for Warrnambool Region and Lakes Entrance Region, which had the lowest length-increments. The only other exceptions to these trends were for several samples with small sample size (n<50) (Tables 4.2.2, 4.2.3). The ‘inter-zone’, ‘inter-region’, and ‘inter-period within region’ comparisons made it possible to detect broad-scale temporal and spatial trends; however, as indicated by the ‘inter-site’, and ‘inter-annual’ comparisons, pooling the data into periods of several years or into regions covering several sites inevitably masks fine-scale inter-annual differences and between-site differences.

This pattern of high spatial and temporal variation in annual length-increment for *J. edwardsii* in waters off Victoria is consistent with patterns for other spiny lobster species (family Panuliridae) such as *Panulirus cygnus* off Western Australia (Joll and Phillips 1984), *J. lalandii* off south-west South Africa (Cruywagen 1997), *J. tristani* at the island group of Tristan da Cunha (Pollock 1991), and with *J. edwardsii* in New Zealand (Annala and Bycroft 1988; McKoy 1985; McKoy and Esterman 1981) and other regions of southern Australia (Linnane *et al.* 2012). Off South Australia, mean annual length-increment of *J. edwardsii* varied markedly during the 3-year period 1994–96 at three separate spatial resolutions depending on adopted scale for pooling data (McGarvey *et al.* 1999), and decreased from the 3-year period 1994–96 to the 3-year period 2006–08 (Linnane *et al.* 2010). Off Tasmania, growth decreases from north to south (Punt *et al.* 1997) and decreases with increasing depth, and translocation of animals from deep water to shallower water resulted in markedly increased growth rates, indicative of plasticity in the growth of *J. edwardsii* (Chandrapavan *et al.* 2010).

Factors affecting growth

Variation in spatial and temporal length-increment growth observed for spiny lobsters in several parts of the world is attributable to a range of factors that relate directly or indirectly to environmental variability. Authors investigating these factors through aquarium experimentation or field observation give differing emphasis to the relative importance of these factors among separate species and places, but nevertheless recognise the likelihood of synergistic effects among the various factors. Type of food available is considered the main factor affecting growth for *P. cygnus* off Western Australia. Oxygen deficiency from the effects of mild to severe eutrophication following nutrient enrichment from upwelling associated with Benguela Current off west-south South Africa has been identified as not only delaying growth or causing shrinkage (Cockcroft and Goosen 1995), but leading to redistribution, crowding and even mass mortality of *J. lalandii*. Growth rates of this species are also shown to be affected by food availability limited by environmental conditions. Ambient-water temperature variation off New Zealand and southern Australia tends to be the most common opinion on the cause of growth variation for *J. edwardsii*. As a social and gregarious species, juvenile *J. edwardsii* under culture conditions grow faster at high densities than under solitary conditions, although in the wild it is postulated that food availability would become a limiting factor under crowded conditions. Evidence of a density-dependent response in growth is from the spatial anti-correlation between male growth rates at 100 mm carapace length and fishery catch rate expressed as number per unit effort off South Australia where a 10% decrease in catch rate gives a 2.5% growth in mass increase (McGarvey *et al.* 1999). Results from the present study are consistent with, but do not prove, a density-dependent response. As growth rates for *J. edwardsii* from late 1970s through late 1990s to the 2000s increased, stock biomass declined. Averaging annual biomass over each period, from late 1970s to late 1990s declined to 63% in WZ and 42% in EZ and by the 2000s biomass was 52% in WZ and 50% in EZ (Walker *et al.* 2013). Other environmental factors considered to exert more subtle effects include light intensity, photoperiod, space, shelter, and inter-specific interactions. Fishing effects on growth of lobsters include capture, handling, and release that can result in physical injury with loss of appendages (Brouwer *et al.* 2006).

Ambient water temperature influences growth of juvenile and adult spiny lobsters such that species inhabiting regions of warm water tend to grow faster than species inhabiting cool water (Booth and Kittaka 2000; Hooker *et al.* 1997). Juvenile *J. lalandii* (10–45 mm initial carapace length) held under experimental conditions at 15°C grew faster than those held at 10°C, because, although there was no difference in the moult-increment, the inter-moult period for those at 15°C was 50% shorter than for those at 10°C (Hazell *et al.* 2001). For *J. edwardsii*, optimal temperature for juvenile growth and survival under culture conditions is 18–20°C (Booth and Kittaka 2000). A recent diver-based tag release-recapture study of growth of juvenile *J. edwardsii* (40–80 mm initial carapace length) in waters off South Australia, Victoria and Tasmania found no difference in growth between males and females up to 40 mm carapace length, but at 50 mm, males grew 1.4 times faster and moulted more frequently than females. At 50–60 mm, female moult-frequency decreases from ~3–4 moults to 1 moult per year, whereas the males continue at the rate of ~3–4 moults per year (Linnane *et al.* 2012).

The onset of maturity appears to inhibit growth in female *J. edwardsii* more than in males (Annala and Bycroft 1988; McGarvey *et al.* 1999) and spatial differences in size of maturity probably reflect spatial differences in growth rate (Gardner *et al.* 2006; Hobday and Ryan 1997; Linnane *et al.* 2008), which is consistent with both growth rates and size-of-maturity estimates in *J. edwardsii* usually decrease with decreasing water temperature (Gardner *et al.* 2006; Hobday and Ryan 1997; Linnane *et al.* 2008). Nevertheless, other factors are likely to have effects such as reduced size-of-maturity of *J. lalandii* from early 1960s to 1980s coinciding with reduced dissolved oxygen associated with the Benguela Current (Pollock and Shannon 1987).

Oxygen deficiency experiments under controlled aquarium conditions show progressively decreased mean moult-increment and increased mean inter-moult period with reducing oxygen saturation for *J. lalandii* (De B Beyers *et al.* 1994). Field observations of more severe oxygen deficiency associated with phytoplankton blooms induced by nutrient enrichment from upwelling related to the Benguela Current off south-west South Africa caused reduced catch rates and redistribution of *J. lalandii* during 1975 and 1976 (Bailey *et al.* 1985) to avoid oxygen-depleted water (Pollock and Shannon 1987). During the 1990s, redistribution of animals from deep to shallow water resulted in overcrowding and exacerbated these effects (Pollock and Shannon 1987) on the west and south coasts of South Africa to cause five reported mass mortalities through oxygen deprivation, ‘walkouts’ and stranding (Cockcroft 2001; Cockcroft *et al.* 2008). In contrast, stocks of *J. edwardsii* off Victoria and South Australia in the vicinity of the Bonny Upwelling (Lewis 1981) might experience the effects from annual cold-water events, such as reduced growth following an extreme upwelling event in 2008 (Linnane *et al.* 2012), but are unlikely to experience severe oxygen deficiency resulting from eutrophication triggered by nutrient-enrichment.

Food availability affected growth of *J. lalandii* off south-west South Africa through a series of environmental perturbations during 1988–95, including the El Niño-related anomaly of 1990–93, which reduced catch rates from the fishery. Upwelling associated with the Benguela Current failed, temperatures rose, primary production fell causing widespread mortality of ribbed mussel (*Aulacomya ater*) (key prey species), and *J. lalandii* moved to deeper less-productive water where growth increment reduced (Pollock *et al.* 1997) with an average shrinkage of 3% (Cockcroft and Goosen 1995). Decreased mean moult-increment and increased inter-moult period coincided with decreased ingestion and increased mortality of *J. lalandii* (De B Beyers *et al.* 1994). Comparison of the contents of the digestive tracts of *Panuliris cygnus* collected from two sites off Western Australia indicated that molluscs formed a major component of the diet at the site of high-growth, whereas coralline algae formed a major component of the diet at the site of slow growth (Joll and Phillips 1984).

High morphologic complexity provides the most suitable habitat for spiny lobsters. As shown at Alacranes Reef in Yucatan, Mexico, densities of *P. argus* are highest in areas of highest complexity of their habitat and depending on the requirements of the animals at any specific life-history stage (Rios-Lara *et al.* 2007). Off Victoria, substrates characterised by differentiation of rock and sediments of various relief and texture are invariant, but associated biota is extremely variable at fine scales and the present community of *J. edwardsii* and its associated biota (Ball *et al.* 2010) are a result of present and past environmental conditions. It is likely that fine-scale spatial and temporal variation in length-increment growth of *J. edwardsii* off the Victorian coast relate to the variation in spatially complex substrates and ever-changing habitats and ambient conditions.

Model suitability

In considering the biological process of growth of harvested lobsters, *J. edwardsii* has a complex life cycle with a long adult phase, late onset of maturity, and external brooding (several months). Eggs hatch and pass through a series of 13−17 instar stages as larvae in the plankton (43 weeks), and then undergo metamorphosis to post-larval puerulus resembling adults (Kittaka 1994) to begin a long benthic phase (many years). Metamorphosis and growth throughout the life cycle is by moulting, under control of the endocrine system, where the old exoskeleton is decalcified by absorption of calcium carbonate prior to it being shed and exposure of a new soft cuticle that subsequently expands and hardens to form a new protective exoskeleton (Wahle and Fogarty 2006). Length-increment growth by moulting has three components of which each varies among the animals in the population: magnitude of moult increment (negative under extreme conditions), magnitude of inter-moult period, and moult timing.

The stock assessment model for the Victorian fishery ignores all the early stages of the complex life history and includes only that part of the *J. edwardsii* population of size ≥60 mm carapace length (Walker *et al.* 2013). Hence, any independent growth model for estimation of growth parameters or growth-transition matrices needs to represent reliably the biological process of growth of only the animals of size ≥60 mm. Two issues in modelling relevant to the growth process of *J. edwardsii* are continuous growth versus discontinuous growth and stochastic growth versus deterministic growth.

Deterministic growth models provide a representation of average length against age (Von Bertalanffy 1938) or average length-increment against length (Fabens 1965) and treat any departure from the average as statistical error. Stochastic models, on the other hand, are more able to embrace the biological variation in length-at-age (Troynikov 1998; Troynikov and Walker 1999) or length-increment-at-length (Punt *et al.* 2006; Troynikov 1998) and provide estimates of parameter and growth-transition matrices that represent the heterogeneity of growth in a population than do deterministic models (Punt *et al.* 2009).

Most growth models assume animals grow continuously, whereas growth of *J. edwardsii* by moulting is stepped and discontinuous, which inevitably produces a high proportion of zero length-increment values in tag release-recapture data. When applying such data in a model, assuming continuous growth biases parameters and growth-transition matrices towards exhibiting slower growth. This phenomenon is demonstrated by the present study through a series of four separate analyses of the data for each of WZ and EZ by sex where the minimum time-at-liberty T was varied such that $T=0.25$, 0.50, 1.00 and 2.00 years. As expected, this usually showed that the pdc move progressively to the right and mean annual length-increment increased with T (Table 4.1.1; Figure 4.1.3). Hence, to reduce this bias, $T=0.50$ years was adopted as a standard for all analyses on the basis that for the size range of the available tag release and recapture, the inter-moult period is about one year and $T=0.50$ years is half this period. In addition to reducing over-representation of zero length-increment in the data for a moulting species, another advantage of $T=0.50$ years is that it reduces biases in length-increment from the effects of tagging, which can cause loss of appendages (Brouwer *et al.* 2006), other physical injuries (Winstanley 1976), displacement from suitable habitat, and physiological stress (Dubula *et al.* 2005). Models that represent stepped discontinuous growth of lobsters exist (Caddy 2003), but at present the models are deterministic and therefore unlikely to perform better than the stochastic models adopted for the present study. However, there is no accepted functional form for moult increment or inter-moult duration (Wahle and Fogarty 2006).

The stochastic models adopted for the present study describe variation in annual length-increment reliably, except for those samples of tag release-recapture data producing annual length-increment pdcs of ‘exponential-decline’ shape. In representing the high proportions of the population exhibiting nil or negligible annual length-increment, the ‘exponential-decline’ shaped pdcs indicate unrealistically large length-increment for a small proportion of the population, and thereby providing unreliable 90% probability intervals for graphical presentation. Whereas some of the problem was small sample size, it also occurred for large samples such as the entire Western Zone and Eastern Zone for females. The issue is more likely associated with the assumption of continuous growth rather than moult process with discontinuous pattern of length-increment.

For the present study, selection of the most appropriate pdf from among gamma, Weibull and log-normal to represent variation among individuals in a population expressed through the random von Bertalanffy–Fabens parameter k in a stochastic model was based on Kullback's information mean or information integral. From analysis of 84 tag release-recapture samples (42 for males and 42 for females), where T =0.50 years and the Richards selectivity function determined from Apollo Bay Escape-gap Experiment for adjustment of effects of SRL length selectivity of lobster pots were standard, the gamma and Weibull pdfs fit the data from the 84 separate samples best with similar frequency for both males and females, whereas the log-normal pdf fitted best for only a minority of the samples. The gamma pdf fit best 37 times (18 for males, 19 for females), Weibull 39 times (18, 21), and log-normal 8 times (6, 2),

Variation in annual length-increment characterised by the three probability pdcs of 'central-dome' shape (mode near centre of pdc), 'left-dome' shape (mode displaced to left with right skew), and 'exponential-decline' shape (high proportion of nil or negligible annual length-increment) differed markedly between males and females. Of the 84 samples, pdc was 'central-dome' shape for 46 samples (39 for males and 7 for females) (i.e. 93% of male samples and 17% of female samples), 'left dome' for 22 samples (1, 21) (i.e. 2%, 50%), and 'exponential decline' shape for 16 samples (2, 14) (i.e. 5%, 33%). This indicates that pdc shape was affected much more by sex of the SRLs and the locality and period of tagging than by selection of pdf.

The spatial and temporal patterns detected by the present study create the challenge of deciding scale for application in length-based models for fishery stock assessment of *J. edwardsii* in Victoria and hence the most appropriate scale for growth-transition matrices. Given that any growth parameter estimates or growth-transition matrices determined from tag length-increment data are affected by locality and period of tag release and tag recapture, there is a need to ensure that the spatial and temporal scales of the growth-transition matrices are compatible with the spatial and temporal scales of available length-frequency composition of SRLs caught in lobster pots collected through fishery monitoring.

Conclusions

The stochastic models applied for the present study performed well where annual length-increment of animals of any specific initial carapace length was 'central-dome' shape or 'left-dome' shape, but not so well for 'exponential-decline' shape where a high proportion of population exhibited nil or negligible annual length-increment. This indicates the need to avoid the usual assumption of continuous growth and to develop specialised stochastic models that account explicitly for the stepped discontinuous moult-increment growth of crustaceans.

Consistent with the results from other studies of growth of spiny lobsters, we conclude that variation in spatial and temporal length-increment growth in *J. edwardsii* off the Victorian coast is remarkably high and that growth is highly plastic depending on habitat suitability and prevailing environmental conditions. General trends were detected where mean annual length-increment increased from the late 1970s, through late 1990s, to 2000s, and increased, with exceptions, from west to east off Victoria. During the 2000s, differences in mean annual length-increment for selected sizes were higher among 13 separate sites than among 6 separate fishing years at one of these sites. Whilst the differences among the sites were marked, the differences among the fishing years were subtle, suggesting the detected trend of progressively increasing mean annual length-increment through the three periods could be explained by differences in the spatial distribution of the tag releases for the three periods rather than by actual temporal increases.

The present study indicates that it is not only important to have separate growth-transition matrices for the different regions of Victoria, but also to vary them over time. Hence, for each of Portland Region, Warrnambool Region, Apollo Bay Region and Queenscliff Region, separately, a growth-transition matrix for each of the males and females is being determined for each year between late 1970s and late 1990s and between late 1990s and 2000s, where the annual matrices determined by interpolation vary inter-annually smoothly from one period to the next. This will enable taking advantage of the flexibility of the SRL stock assessment model, which includes facility to vary growth-transition matrices spatially and temporally simultaneously.

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Appendix 1

Modelling growth

Stochastic growth models and method for correction of gear selectivity bias applied in the present study were developed in Troynikov (1998, 1999). This appendix mainly repeats the description of the models adopted for an earlier study analysing tag length-increment data from the Victorian rock lobster fishery (Punt *et al.* 2006). As described below, the present study applied the exact same models and method except the truncated normal pdf was replaced with the Weibull pdf (Appendix 1).

The probability of an animal in size-class i growing into size-class j over a time period Δt is based on the assumption that the growth of an individual rock lobster follows a von Bertalanffy growth curve, and that the von Bertalanffy–Fabens growth curve parameter k varies among individuals according to some pre-specified probability distribution i.e.:

$$l_p^c = l_p^r + (\ell_\infty - l_p^r)(1 - e^{-k_p \Delta t_p}) \tag{1}$$

where l_p^r is the carapace length of animal p when released, l_p^c is the carapace length of animal p when recaptured, Δt_p is the time animal p was at liberty, and k_p is the von Bertalanffy–Fabens parameter for animal p:

$$k_p \sim g() \tag{2}$$

where g is the probability distribution for the von Bertalanffy–Fabens parameter, and ℓ_∞ is the maximum asymptotic carapace length in the population.

The analysis is based on the assumption that k varies among individuals. This choice is largely arbitrary and, given the high correlation between k and ℓ_∞, similar results would have been obtained had it been assumed that ℓ_∞ varied among individuals and k was the same for all animals.

Equation 3 is maximized to estimate ℓ_∞ and the parameters of the distribution for the von Bertalanffy–Fabens k parameter (Troynikov 1998).

$$L = \prod_p \frac{g(-\ell\text{n}[1 - (l_p^c - l_p^r)/(\ell_\infty - l_p^r)]/\Delta t_p)}{\Delta t_p(\ell_\infty - l_p^c)}. \tag{3}$$

The denominator of Equation (3) is the Jacobian of the transformation of variables from k to length- increment growth $l_p^c - l_p^r$.

Three choices for the distribution g considered are log-normal, gamma, and Weibull (Equations 4a-4c):

$$g(k) = \frac{1}{\sqrt{2\pi}\sigma k} e^{-\frac{(\ell\text{n}k-\mu)^2}{2\sigma^2}}, \tag{4a}$$

$$g(k) = \frac{\beta^\alpha}{\Gamma(\alpha)} k^{\alpha-1} e^{-\beta k}, \text{ and} \tag{4b}$$

$$g(k) = \eta\rho^{-\eta} k^{(\eta-1)} \exp^{-(\frac{k}{\rho})^\eta} \tag{4c}$$

where μ, σ, α, β, η and ρ are the parameters that determine the mean and variance of the distribution for the von Bertalanffy–Fabens parameter k where none of these distributions allow the possibility of negative values for k.

To account for gear selectivity of escape-gaps in rock lobster pots, an estimator developed for the case where growth increments are gamma distributed and gear selectivity governed by a gamma function (Dow 1992) was generalised for arbitrarily-defined selectivity patterns and arbitrary distributions for length-increment (Troynikov 1999), where the likelihood maximized to find the estimates of the parameters of the model when selectivity as a function of length is defined by the function S_l:

$$L = \prod_p \frac{S_{l_p^c}\, g(-\ell\text{n}[1-(l_p^c - l_p^r)/(\ell_\infty - l_p^r)]/\Delta t_p)}{(\ell_\infty - l_p^c)\int_{l_p^r}^{\ell_\infty} \frac{S_l}{(\ell_\infty - l)}\, g(-\ell\text{n}[1-(l - l_p^r)/(\ell_\infty - l_p^r)]/\Delta t_p)\, dl} \tag{5}$$

Size selectivity of rock lobster pots using the Richards model is given by:

$$S_{\boldsymbol{\ell}} = \left(\frac{e^{a+b\boldsymbol{\ell}}}{1+e^{a+b\boldsymbol{\ell}}} \right)^{1/\delta} \tag{6}$$

where a, b, and δ define the relationship between size and selectivity and where estimates for a, b, and δ were obtained from the results of an experiment conducted in Apollo Bay for lobster pots with 60 mm escape-gaps (mandated in Victoria) (Treble *et al.* 1998).

Calculating the size-transition matrix

The size-transition matrix $\{X_{i,j} : j = 1..m\}$ where m is the number of size-classes, defines the probability of an animal in size-class *i* growing into size-class j over a time-step Δt. Given an estimate of $\boldsymbol{\ell}_\infty$, and estimates for the parameters of the distribution for *k*, the values for the $X_{i,j}$ are determined using the equation:

$$X_{i,j} = \frac{1}{h\Delta t}\iint \frac{1}{(\ell_\infty - y)}\, g(-\ell\text{n}[1-(y-x)/(\ell_\infty - y)]/\Delta t)\, dy\, dx \tag{7}$$

where y is a size in size-class j, x is a size in size-class i, and h is the width of the size classes.

By definition, $\sum_j X_{i,j} = 1$. The estimates of the growth parameters obtained by maximizing Equation 5 are substituted into Equation 7 to account for the impact of gear selectivity. Equation 7 is defined in terms of an arbitrary time-step and an arbitrary size-class width; the results in this paper pertain to an annual time-step and the size-classes on which assessments of rock lobsters off Victoria are based. The uncertainty associated with the estimates of $\boldsymbol{\ell}_\infty$ and the parameters of the distribution for k can be quantified by integrating Equation 7 over the distribution for the statistical error associated with the estimates of its parameter.

Table 1. Site name and site code for annual fixed-site survey

Sites listed west to east (see Figure 2); in Western Zone data from a site near Port Campbell surveyed on one day during 2004 were pooled with site ML and data from another abandoned site referred to as Port Fairy East were excluded from present study; three of original five fixed-sites in Eastern Zone were abandoned and excluded from present study.

Zone	Region	Site name	Site code	Year first sampled
Western	Portland	Discovery Bay West	DBW	2002
		Discovery Bay Deepwater	DBD	2007
		Discovery Bay East	DBE	2002
		Portland	P	2002
	Warrnambool	Port Fairy West	PFW	2002
		Warrnambool Deepwater	WD	2007
		Warrnambool West	WW	2002
		Warrnambool East	WE	2002
		Warrnambool South	WS	2002
	Apollo Bay	Big Reef	BR	2002
		Moonlight Head	ML	2005
		Nine Mile Reef	NM	2002
Eastern	Queenscliff	Torquay	T	1996
		Ocean Grove	OG	1996

Table 2. Number of tagged SRLs released off Victoria from 1975–76 to 2010–11

SRL, southern rock lobster; the table excludes tag release data from multiple recapture and release.

Zone	Scientific observation	Number of SRLs tagged & released
First period (1975–76 to 1981–82)		
West	Research project	6438
East	Research project	2544
Combined	Research project	8982
Second period (1991–92 to 2010–11)		
West	Commercial operation	18256
East	Commercial operation	4047
Combined	Commercial operation	22303
West	Fixed-site survey	42037
East	Fixed-site survey	5965
Combined	Fixed-site survey	48002
Total for secomd period		70305
Periods combined		
West		66731
East		12556
Combined		79287

Table 3.1. Number of recaptured tagged SRLs by tag release fishing year, sex and site type in each region

SRL, southern rock lobster; fishing year, 1 November–31 October; fixed-site, fixed-site survey tag release; other, all other sites of tag release; required data are after removal of uncertainty related to incorrect tag number, to different sex of SRL between tag release and tag recapture, to missing length-increment, and to length-increment <–2 mm (negative growth) between date of tag release and date of tag recapture.

Fishing year or selected period	Number of recaptured tagged SRLs with required data for fixed-site survey and other sources of data in each region																							
	Portland Region				Warrnambool Region				Apollo Bay Region				Queenscliff Region				San Remo Region				Lakes Entrance Region			
	Male		Female		Male		Female		Male		Female		Male		Female		Male		Female		Male		Female	
	Fixed-site	Other	Fixed-site	Other	Fixed-site	Other	Fixed-site	Other	Fixed-site	Other	Fixed-site	Other	Fixed-site	Other	Fixed-site	Other	Fixed-site	Other	Fixed-site	Other	Fixed-site	Other	Fixed-site	Other
Fishing year																								
1975–76		386		568																6				
1976–77		23		94		4		10						81		148								
1977–78		49		126		9		18		39		62		25		29								
1978–79				2				1				2				4						14		53
1979–80				3		2		1														5		41
1980–81																1								2
1981–82																								4
1991–92										3		2												
1992–93																								
1993–94		18		38		18		59		25		43		38		81		1		1				
1994–95		99		100		38		108		109		184		9		37		8		28		2		2
1995–96		104		118		8		17		79		210	10	57	25	78				2		29		40
1996–97		64		109				3		9		35	57	7	49	4				3		14		9
1997–98		61		84		39		22		3		5	55		59	4						9		2
1998–99		18		19						14		3	26		36	1		1		5		16		10
1999–00		1		6				2		4		8	15	17	22	8						12		3
2000–01				2						1		4	17		12							14		2
2001–02	178	6	205	8	121	7	179	8	23		36		13	1	9		2		1					
2002–03	171		187		150	6	202	11	20	9	23	17	15	3	22	3								
2003–04	120		112	1	67	1	138	1	33	18	52	15	9	3	17	5								
2004–05	107		129	3	122	6	194	6	28		65		12		7									
2005–06	91		74	3	133		175		24		39		6		4	1								
2006–07	133	40	110	43	115	52	148	57	40	1	55		2		11	2								
2007–08	13	10	17	15	41	6	67	8	5		12		3		7									
2008–09	19	3	31	2	75	28	111	30	25	1	57		14		9									
2009–10	32	1	21	2	49	21	63	29	22		25		8	1	5									
2010–11	12	6	11	4	4	2	4	8	4		12		6		5									
Selected periods for 'inter-site comparison'																								
WZ from 2001–02 to 2010–11	876		897		877		1281		224		376													
EZ from 1995–96 to 2010–11													268		299									
Selected periods for 'inter-period comparison'																								
1975–76 to 1977–78	0	458	0	788	0	13	0	28	0	39	0	62	0	106	0	177	0	0	0	6	0	0	0	0
1994–95 to 1998–99	0	346	0	430	0	85	0	150	0	214	0	437	148	73	169	124	0	9	0	38	0	70	0	63
2002–03 to 2010–11	698	60	692	73	756	122	1102	150	201	29	340	32	75	7	87	11	0	0	0	0	0	0	0	0
Sum of selected periods	698	864	692	1291	756	220	1102	328	201	282	340	531	223	186	256	312	0	9	0	44	0	70	0	63
All fishing years																								
1975–76 to 2010–11	876	889	897	1350	877	247	1281	399	224	315	376	590	268	242	299	406	2	10	1	45	0	115	0	168

Table 3.2. Number of recaptured tagged SRLs by release fishing year and sex in each region

SRL, southern rock lobster; fishing year, 1 November–31 October; required data are after removal of uncertainty related to incorrect tag number, to different sex of SRL between tag release and tag recapture, to missing length-increment, and to length-increment <–2 mm (negative growth) between date of tag release and date of tag recapture.

Fishing year or selected period	Number of recaptured tagged SRLs with required data for fixed-site survey and other sources of data in each region																				
	Portland Region			Warrnambool Region			Apollo Bay Region			Queenscliff Region			San Remo Region			Lakes Entrance Region			Total		
	Males	Females	Total	Males	Females	Total	Males	Females	Total	Males	Females	Total	Males	Females	Total	Males	Females	Total	Males	Females	Total
Fishing year																					
1975–76	386	568	954											6	6				386	574	960
1976–77	23	94	117	4	10	14				81	148	229							108	252	360
1977–78	49	126	175	9	18	27	39	62	101	25	29	54							122	235	357
1978–79		2	2		1	1		2	2		4	4				14	53	67	14	62	76
1979–80		3	3	2	1	3										5	41	46	7	45	52
1980–81											1	1					2	2	0	3	3
1981–82																	4	4	0	4	4
1991–92							3	2	5										3	2	5
1992–93																			0	0	0
1993–94	18	38	56	18	59	77	25	43	68	38	81	119	1	1	2				100	222	322
1994–95	99	100	199	38	108	146	109	184	293	9	37	46	8	28	36	2	2	4	265	459	724
1995–96	104	118	222	8	17	25	79	210	289	67	103	170		2	2	29	40	69	287	490	777
1996–97	64	109	173		3	3	9	35	44	64	53	117		3	3	14	9	23	151	212	363
1997–98	61	84	145	39	22	61	3	5	8	55	63	118				9	2	11	167	176	343
1998–99	18	19	37				14	3	17	26	37	63	1	5	6	16	10	26	75	74	149
1999–00	1	6	7		2	2	4	8	12	32	30	62				12	3	15	49	49	98
2000–01		2	2				1	4	5	17	12	29				14	2	16	32	20	52
2001–02	184	213	397	128	187	315	23	36	59	14	9	23	2	1	3				351	446	797
2002–03	171	187	358	156	213	369	29	40	69	18	25	43							374	465	839
2003–04	120	113	233	68	139	207	51	67	118	12	22	34							251	341	592
2004–05	107	132	239	128	200	328	28	65	93	12	7	19							275	404	679
2005–06	91	77	168	133	175	308	24	39	63	6	5	11							254	296	550
2006–07	173	153	326	167	205	372	41	55	96	2	13	15							383	426	809
2007–08	23	32	55	47	75	122	5	12	17	3	7	10							78	126	204
2008–09	22	33	55	103	141	244	26	57	83	14	9	23							165	240	405
2009–10	33	23	56	70	92	162	22	25	47	9	5	14							134	145	279
2010–11	18	15	33	6	12	18	4	12	16	6	5	11							34	44	78
Selected periods for 'inter-period comparison'																					
1975–76 to 1977–78	458	788	1246	13	28	41	39	62	101	106	177	283	0	6	6	0	0	0	616	1061	1677
1994–95 to 1998–99	346	430	776	85	150	235	214	437	651	221	293	514	9	38	47	70	63	133	945	1411	2356
2002–03 to 2010–11	758	765	1523	878	1252	2130	230	372	602	82	98	180	0	0	0	0	0	0	1948	2487	4435
Sum of selected periods	1562	1983	3545	976	1430	2406	483	871	1354	409	568	977	9	44	53	70	63	133	3509	4959	8468
All Fishing years																					
1975–76 to 2010–11	1765	2247	4012	1124	1680	2804	539	966	1505	510	705	1215	12	46	58	115	168	283	4065	5812	9877

Table 4.1.1. Comparison of SRL sample size and estimates of growth parameters and mean annual length-increment among the two zones (with sensitivity tests for selectivity function and *T*) and six regions by sex for all years

SRL, southern rock lobster; all years, fishing years from 1975–76 to 2010 −11; fishing year, 1 November–31 October; *T*, minimum period at liberty for selection from available data for inclusion in analysis; ℓ_∞, theoretical maximum carapace length; pdf, probability density function; *k*, brody growth rate; se, standard error on ℓ_∞; sd, standard deviation of distribution of *k*; pdc, probability density curve; na, not available because the pdc could not be estimated.

Zone or region	Fishing years for tag release	Sex	Sample size			ℓ_∞ (mm)	pdf for distribution of *k*	E[*k*] (median) ($year^{-1}$)	sd [*k*] ($year^{-1}$) (%)	Annual length-increment pdc shape	Upper pdc percentile presented (%)	Mean annual length-increment for three initial carapace lengths (mm)		
			Non-selected	Selected	Per cent selected							60 mm	80 mm	100 mm
Standard T=0.5 and standard Apollo Bay escape-gap selectivity function (reduced to 0.25 years for females in San Remo Region)														
Western Zone	All years	Male	3428	2724	79	191	Gamma	0.155	57	Central dome	95	18	16	13
		Female	4893	4216	86	151	Gamma	0.087	90	Exponential decline	90	7	6	4
Eastern Zone	All years	Male	609	398	65	220	Weibull	0.137	49	Central dome	95	20	18	15
		Female	948	637	67	170	Gamma	0.097	100	Exponential decline	90	10	8	6
Portland Region	All years	Male	1765	1331	75	174	Weibull	0.196	52	Central dome	95	20	16	13
		Female	2242	1911	85	149	Weibull	0.094	81	Left dome	95	8	6	4
Warrnambool Region	All years	Male	1124	961	85	185	Gamma	0.159	51	Central dome	95	18	15	12
		Female	1680	1505	90	151	Gamma	0.075	101	Exponential decline	90	6	5	4
Apollo Bay Region	All years	Male	539	432	80	195	Log-normal	0.174	52	Central dome	95	21	18	15
		Female	966	800	83	295	Weibull	0.025	80	Exponential decline	80	6	5	5
Queenscliff Region	All years	Male	510	305	60	235	Weibull	0.124	48	Central dome	95	20	18	16
		Female	705	414	59	172	Weibull	0.126	76	Left dome	95	13	10	8
San Remo Region	All years	Male	12	8	67	242	Gamma	0.134	22	Central dome	95	23	20	18
		Female	47	43	91	176	Gamma	0.081	194	Exponential decline	55	8	7	5
Lakes Entrance Region	All years	Male	87	85	98	225	Weibull	0.117	37	Central dome	95	18	16	14
		Female	195	193	99	133	Weibull	0.112	82	Left dome	95	7	5	3
Test T=0.25 and standard Apollo Bay escape-gap selectivity function														
Western Zone	All years	Male	3428	3011	88	202	Weibull	0.131	66	Left dome	95	17	15	12
		Female	4893	4408	90	151	Weibull	0.087	95	Exponential decline	90	7	6	4
Eastern Zone	All years	Male	609	499	82	206	Weibull	0.158	73	Left dome	95	20	18	15
		Female	948	772	81	464	Gamma	0.015	131	Exponential decline	na	7	6	5
Test T=1.00 and standard Apollo Bay escape-gap selectivity function														
Western Zone	All years	Male	3428	1416	41	185	Gamma	0.175	45	Central dome	95	20	17	13
		Female	4893	2458	50	207	Weibull	0.094	143	Exponential decline	85	5	5	4
Eastern Zone	All years	Male	609	273	45	219	Weibull	0.139	50	Central dome	95	20	18	15
		Female	948	511	54	171	Weibull	0.092	88	Left dome	95	10	8	6
Test T=2.00 and standard Apollo Bay escape-gap selectivity function														
Western Zone	All years	Male	3428	338	10	196	Weibull	0.131	66	Central dome	95	18	16	13
		Female	4893	1276	26	151	Gamma	0.077	68	Left dome	95	7	5	4
Eastern Zone	All years	Male	609	87	14	233	Weibull	0.123	32	Central dome	95	20	18	15
		Female	948	272	29	174	Weibull	0.078	73	Left dome	95	8	7	5
Test T=0.50 and test Portland escape-gap selectivity function														
Western Zone	All years	Male	3428	2724	79	237	Weibull	0.103	54	Central dome	95	17	15	13
		Female	4893	4216	86	151	Gamma	0.099	88	Exponential decline	95	8	6	5
Eastern Zone	All years	Male	609	398	65	208	Weibull	0.164	51	Central dome	95	21	18	16
		Female	948	637	67	170	Weibull	1.078	93	Exponential decline	95	11	9	7

Table 4.2.1. Comparison of SRL sample size and estimates of growth parameters and mean annual length-increment among three periods of tag release within each region by sex

SRL, southern rock lobster; fishing year, 1 November–31 October; ℓ_∞, theoretical maximum carapace length; pdf, probability density function; k, brody growth rate; se, standard error on ℓ_∞; sd, standard deviation of distribution of k; pdc, probability density curve; T, minimum period at liberty for selection from available data for inclusion in analysis is standard at 0.50 years (reduced to 0.25 years for each of males and females for Late 1990s in San Remo Region); Late 1970s, from 1975–76 to 1978–79; Late 1990s, from 1994–95 to 1998–99; and All 2000s, from 2001–02 to 2010–11; lobster-pot selectivity-adjustment based on Richards selectivity function for Apollo Bay Escape-gap Experiment.

Region	Period for tag release	Sex	Sample size			ℓ_∞ (mm)	pdf for distribution of k	E[k] (median) (year^{-1})	sd [k] (year^{-1}) (%)	Annual length-increment pdc shape	Upper pdc percentile presented (%)	Mean annual length-increment for three initial carapace lengths (mm)		
			Non-selected	Selected	Per cent selected							60 mm	80 mm	100 mm
Western Zone														
Portland	Late 1970s	Male	458	273	60	181	Gamma	0.134	102	Exponential decline	90	14	12	10
		Female	793	606	76	153	Gamma	0.075	87	Left dome	95	6	5	4
	Late 1990s	Male	346	240	69	169	Weibull	0.205	48	Central dome	95	21	17	13
		Female	321	256	80	150	Gamma	0.082	98	Exponential decline	90	7	5	4
	Most 2000s	Male	758	646	85	222	Weibull	0.118	39	Central dome	95	18	16	13
		Female	765	708	93	124	Weibull	0.214	81	Left dome	95	12	8	4
Warrnambool	Late 1970s	Male	13	10	77	274	Log-normal	0.095	26	Central dome	95	19	17	16
		Female	29	22	76	133	Weibull	0.167	85	Left dome	95	11	8	5
	Late 1990s	Male	85	69	81	264	Weibull	0.100	43	Central dome	95	18	16	14
		Female	147	113	77	154	Weibull	0.072	129	Exponential decline	80	6	5	4
	Most 2000s	Male	878	763	87	176	Weibull	0.177	46	Central dome	95	19	15	12
		Female	1252	1163	93	145	Weibull	0.089	98	Exponential decline	90	7	5	4
Apollo Bay	Late 1970s	Male	39	16	41	326	Log-normal	0.068	97	Left dome	95	17	16	14
		Female	64	40	63	141	Gamma	0.114	102	Exponential decline	90	8	6	4
	Late 1990s	Male	214	160	75	177	Gamma	0.226	43	Central dome	95	23	19	15
		Female	437	339	78	137	Gamma	0.141	73	Left dome	95	10	7	5
	Most 2000s	Male	230	216	94	252	Gamma	0.099	42	Central dome	95	18	16	14
		Female	372	356	96	130	Gamma	0.202	80	Left dome	95	12	9	5
Eastern Zone														
Queenscliff	Late 1970s	Male	106	28	26	162	Gamma	0.317	108	Exponential decline	90	24	19	15
		Female	182	62	34	142	Weibull	0.184	120	Exponential decline	90	12	9	6
	Late 1990s	Male	221	158	71	231	Weibull	0.130	33	Central dome	95	21	18	16
		Female	293	215	73	172	Weibull	0.120	78	Left dome	95	12	10	8
	Most 2000s	Male	82	67	82	227	Log-normal	0.173	45	Central dome	95	26	23	20
		Female	98	63	64	151	Weibull	0.238	48	Central dome	95	19	15	11
San Remo	Late 1990s	Male	9	9	100	231	Log-normal	0.180	29	Central dome	95	28	25	22
		Female	36	32	89	166	Weibull	0.135	241	Exponential decline	60	10	8	6
Lakes Entrance	Late 1970s	Male	14	14	100	186	Weibull	0.219	17	Central dome	95	25	21	17
		Female	52	52	100	127	Gamma	0.089	118	Exponential decline	90	5	4	2
	Late 1990s	Male	63	62	98	216	Weibull	0.123	40	Central dome	95	18	16	13
		Female	56	56	100	136	Gamma	0.106	76	Left dome	95	12	10	8

Table 4.2.2. Order of regions in mean annual length-increment for 80 mm southern rock lobsters

Mean annual length-increments for 80-mm southern rock lobsters are for each region all years from Table 4.1.1 and for each period within each each region from Table 4.2.1; >, 0.0–0.9 mm, >>, 1.0–1.9 mm, etc, indicate magnitude of difference in mean annual length-increment between regions; lobster-pot selectivity-adjustment based on Richards selectivity function for Apollo Bay Escape-gap Experiment; T, minimum period at liberty for selection from available data for inclusion in analysis is standard at 0.50 years (reduced to 0.25 years for each of males and females for Late 1990s in San Remo Region); Late 1970s, from 1975–76 to 1978–79; Late 1990s, from 1994–95 to 1998–99; and All 2000s, from 2001–02 to 2010–11.

Sex	Period	Mean annual length-increment (mm) (left with sample size below right) for each region during each period by sex										
		Warrnambool		Lakes Entrance		Portland		Apollo Bay		Queenscliff		San Remo
	1970s	17	<<	21	>>>>>>	12	<<<<	16	<<<<	19		–
		10		14		273		16		28		0
Male	1990s	16	<	16	<	17	<<	19	<	18	<<<<<<<	25
		69		62		240		160		158		9
	2000s	15		–	<	16	<	16	<<<<<<<	23		–
		763		0		646		230		67		0
	Combined	15	<	16	<<	16	<<	18	<	18	<<<<<	20
		1124		85		1331		432		305		9
	1970s	8	>>>>	4	<<	5	<<	6	<	9		–
		22		52		606		40		62		0
Female	1990s	5	<	10	>	5	<<	7	<	10	>	8
		113		56		256		339		215		32
	2000s	5		–	<<<	8	<	9	<<<<<<<	15		–
		1163		0		708		356		63		0
	Combined	5	<	5	<<	6	>	5	<<<<<<	10	<<	7
		1505		193		1911		800		218		43

Table 4.2.3. Order of periods based on mean annual length-increment for 80-mm southern rock lobsters

Mean annual length-increments for 80-mm southern rock lobsters are for each region all years from Table 4.1.1 and for each period within each each region from Table 4.2.1; >, 0.0–0.9 mm, >>, 1.0–1.9 mm, etc, indicate magnitude of difference in mean annual length-increment between periods; lobster-pot selectivity-adjustment based on Richards selectivity function for Apollo Bay Escape-gap Experiment; T, minimum period at liberty for selection from available data for inclusion in analysis is standard at 0.50 years (reduced to 0.25 years for each of males and females for Late 1990s in San Remo Region); Late 1970s, from 1975–76 to 1978–79; Late 1990s, from 1994–95 to 1998–99; and All 2000s, from 2001–02 to 2010–11.

Region	Mean annual length-increment (mm) (left with sample size below right) for each period in each region by sex												
	Male							Female					
	1970s		1990s		2000s	All years		1970s		1990s		2000s	All years
Warrnambool	17 10	>>	16 69	>	15 763	15 1124		8 22	>>>	5 113	<	5 116	5 1505
Lakes Entrance	21 14	>>>>>	16 62		– 0	16 85		4 52	<<	5 56		– 0	5 193
Portland	12 273	<<<<<<	17 240	>>	16 646	16 1331		5 606	<	5 256	<<<	8 708	6 1911
Apollo Bay	16 16	<<<	19 160	>>>	16 230	18 432		6 40	<	7 339	<<	9 356	5 800
Queenscliff	19 28	<	18 158	<<<<	23 67	18 305		9 62	<<<	10 215	<<<<<	15 63	10 218
San Remo	– 0		25 9		– 0	20 8		– 0		8 32		– 0	7 43

Table 4.3.1. Comparison of sample size, estimates of SRL growth parameters and mean annual length-increment for each sex among fixed-sites within region for period 2002 –11 in WZ and 1996–11 in EZ

WZ, Western Zone; EZ, Eastern Zone; SRL, southern rock lobster; fishing year, 1 November–31 October; T, minimum period at liberty for selection from available data for inclusion in analysis is standard at 0.50 years (reduced to 0.10 years for males at WD); ℓ_∞, maximum carapace length; pdf, probability density function; k, brody growth rate; se, standard error on ℓ_∞; sd, standard deviation of distribution of k; pdc, probability density curve; lobster-pot selectivity-adjustment based on Richards selectivity function for Apollo Bay Escape-gap Experiment.

Region	Fixed-site name (with fixed-site code in parentheses)	Sex	Sample size			ℓ_∞ (mm)	pdf for distribution of k	E[k] (median) (year^{-1})	sd [k] (year^{-1}) (%)	Annual length-increment pdc shape	Upper ppd percentile presented (%)	Mean annual length-increment for three initial carapace lengths (mm)		
			Non-selected	Selected	Per cent selected							60 mm	80 mm	100 mm
Western Zone														
Portland	Discovery Bay West (DBW)	Male	201	157	78	147	Gamma	0.387	51	Central dome	95	27	21	15
		Female	136	110	81	124	Gamma	0.330	80	Central dome	95	17	12	6
	Discovery Bay Deep (DBD)	Male	40	33	83	380	Weibull	0.048	38	Central dome	95	15	14	13
		Female	61	55	90	121	Weibull	0.328	78	Central dome	95	16	11	6
	Discovery Bay East (DBE)	Male	551	489	89	145	Gamma	0.350	39	Central dome	95	25	19	13
		Female	616	597	97	122	Gamma	0.211	70	Left dome	95	11	8	4
	Portland (P)	Male	87	72	83	148	Gamma	0.401	66	Central dome	95	27	21	15
		Female	95	93	98	126	Gamma	0.298	56	Central dome	95	16	11	6
Warrnambool	Port Fairy West (PFW)	Male	183	157	86	231	Gamma	0.109	33	Central dome	95	18	16	13
		Female	247	228	92	119	Weibull	0.294	70	Central dome	95	14	9	5
	Warrnambool West (WW)	Male	191	166	87	159	Weibull	0.241	45	Central dome	95	21	17	12
		Female	235	214	91	135	Weibull	0.126	83	Left dome	95	8	6	4
	Warrnambool East (WE)	Male	207	187	90	261	Weibull	0.092	40	Central dome	95	18	16	14
		Female	226	218	96	140	Weibull	0.168	78	Left dome	95	12	9	6
	Warrnambool Deepwater (WD)	Male	50	50	100	238	Log-normal	0.072	33	Central dome	95	12	11	9
		Female	92	91	99	113	Gamma	0.219	127	Exponential decline	90	9	6	2
	Warrnambool South (WS)	Male	236	212	90	170	Gamma	0.198	59	Central dome	95	19	16	12
		Female	465	455	98	151	Gamma	0.064	94	Exponential decline	90	5	4	3
Apollo Bay	Moonlight Head (MH)	Male	64	62	97	157	Weibull	0.320	40	Central dome	95	26	21	15
		Female	97	85	88	128	Log-normal	0.268	76	Left dome	95	15	11	6
	Nine Mile Reef (NM), Big Reef (BR)	Male	160	152	95	157	Gamma	0.295	50	Central dome	95	24	19	14
		Female	279	279	100	182	Gamma	0.066	81	Left dome	95	8	6	5
Eastern Zone														
Queenscliff	Torquay (T)	Male	120	82	68	222	Weibull	0.131	42	Central dome	95	20	17	15
		Female	138	85	62	151	Weibull	0.200	66	Central dome	95	16	12	9
	Ocean Grove (OG)	Male	140	91	65	218	Gamma	0.167	28	Central dome	95	24	21	18
		Female	149	103	69	151	Gamma	0.270	44	Central dome	95	21	16	12

Table 4.4.1. Comparison of SRL sample size and estimates of growth parameters and mean annual length-increment among six fishing years of tag release at Site DBE by sex

SRL, southern rock lobster; six fishing years (1 November–31 October) are from 2001−02 to 2006–07; DBE, Discovery Bay East fixed site (Portland Region); ℓ_∞, maximum carapace length; pdf, probability density function; $\boldsymbol{k}$, brody growth rate; se, standard error on ℓ_∞; sd, standard deviation of distribution of $\boldsymbol{k}$; $\boldsymbol{T}$, minimum period at liberty for selection from available data for inclusion in analysis is standard at 0.50 years; pdc, probability density curve; lobster-pot selectivity-adjustment based on Richards selectivity function for Apollo Bay Escape-gap Experiment.

Region	Fishing years for tag release	Sex	Sample size			ℓ_∞ (mm)	pdf for distribution of $\boldsymbol{k}$	**E[k]** (median) (year^{-1})	**sd [k]** (year^{-1}) (%)	Annual length-increment pdc shape	Mean annual length-increment for three initial carapace lengths (mm)		
			Non-selected	Selected	Per cent selected						60 mm	80 mm	100 mm
Western Zone													
Portland	2001–02	Male	117	105	90	142	Gamma	0.411	44	Central dome	26.8	20.3	13.7
		Female	150	148	99	121	Weibull	0.225	67	Left dome	11.9	8.0	4.1
	2002–03	Male	132	103	78	147	Gamma	0.357	37	Central dome	25.6	19.7	13.8
		Female	160	147	92	126	Weibull	0.163	62	Left dome	9.6	6.7	3.8
	2003–04	Male	89	80	90	139	Gamma	0.412	35	Central dome	26.2	19.6	13.0
		Female	82	82	100	123	Weibull	0.194	72	Left dome	10.7	7.3	3.9
	2004–05	Male	86	78	91	133	Gamma	0.561	43	Central dome	30.1	21.8	13.5
		Female	108	104	96	117	Log-normal	0.317	56	Left dome	14.8	9.6	4.4
	2005–06	Male	53	53	100	138	Weibull	0.100	43	Central dome	27.9	20.7	13.6
		Female	48	48	100	116	Weibull	0.342	84	Left dome	14.8	9.5	4.2
	2006–07	Male	63	60	95	176	Weibull	0.177	46	Central dome	25.2	19.1	13.0
		Female	47	47	100	119	Gamma	0.281	72	Left dome	13.5	8.9	4.3

Table 5.1. Percentage of legal-sized SRLs with lengths exceeding tag estimated L_{Max}

SRL, southern rock lobster; L_{Max}, maximum carapace length; LML, legal minimum length (110 mm carapace length for males and 105 mm carapace length for females); in port, in-port sampling during fishing years from 1978–79 to 2010–11; onboard, onboard observer program during fishing years from 2004–05 to 2010–11; survey, fixed-site survey during fishing years from 2001–02 to 2010–11 (see Table 5.2 for sample size).

Region	Sex	L_{Max} (mm)	First 5-mm length-class >L_{Max} in growth-transition matrix	Per cent of SRLs of length > LML and in 5-mm length-classes > L_{Max} for each data source		
				In-port	On-board	Survey
Portland	Male	148	150–154	2.1	1.9	0.8
	Female	126	130–134	0.5	0.7	0.1
Warnambool	Male	261	265–69	0.0	0.0	0.0
	Female	151	155–59	0.0	0.0	0.0
Apollo Bay	Male	157	160–164	0.7	9.3	1.2
	Female	182	185–189	0.0	0.0	0.0
Queenscliff	Male	222	225–229	0.0	0.0	0.0
	Female	151	155–159	4.6	5.6	0.4

Table 5.2. Sample size by sex of SRLs and their size relative to LML for each source of monitoring data

SRL, southern rock lobster; LML, legal minimum length; in port, in-port sampling during fishing years from 1978 –79 to 2010–11; onboard, onboard observer program during fishing years from 2004–05 to 2010–11; survey, fixed-site survey during fishing years from 2001–02 to 2010–11.

Region	Sex	Size	No. SRLs by sex and size relative to LML for each data source			Per cent SRLs by sex and size relative to LML for each data source		
			In-port	On-board	Survey	In-port	On-board	Survey
Portland	Male	<LML	0	3281	7892	0	47	70
		≥LML	108035	3669	3318	100	53	30
		Total	108035	6950	11210	100	100	100
	Female	<LML	0	4605	9004	0	67	80
		≥LML	58955	2254	2290	100	33	20
		Total	58955	6859	11294	100	100	100
Warnambool	Male	<LML	0	12086	9394	0	41	70
		≥LML	16092	17618	4056	100	59	30
		Total	16092	29704	13450	100	100	100
	Female	<LML	0	15846	12768	0	52	82
		≥LML	8150	14443	2767	100	48	18
		Total	8150	30289	15535	100	100	100
Apollo Bay	Male	<LML	0	358	3598	0	26	57
		≥LML	2281	1010	2713	100	74	43
		Total	2281	1368	6311	100	100	100
	Female	<LML	0	458	4508	0	39	62
		≥LML	843	704	2768	100	61	38
		Total	843	1162	7276	100	100	100
Queenscliff	Male	<LML	0	634	1487	0	22	28
		≥LML	825	2275	3869	100	78	72
		Total	825	2909	5356	100	100	100
	Female	<LML	0	178	847	0	7	18
		≥LML	825	2275	3858	100	93	82
		Total	825	2453	4705	100	100	100

Table 5.3. Sex ratio of SRLs by size relative to LML for each source of monitoring data

SRL, southern rock lobster; LML, legal minimum length; in port, in-port sampling during fishing years from 1978–79 to 2010–11; onboard, onboard observer program during fishing years from 2004–05 to 2010–11; survey, fixed-site survey during fishing years from 2001–02 to 2010–11 (see Table 5.2 for sample size).

Region	Size	Sex	Proportion of SRLs by sex and size relative to LML		
			In-port	On-board	Survey
Portland	<LML	Male	–	0.42	0.47
		Female	–	0.58	0.53
	≥LML	Male	0.65	0.62	0.59
		Female	0.35	0.38	0.41
	Total	Male	–	0.50	0.50
		Female	–	0.50	0.50
Warnambool	<LML	Male	–	0.43	0.42
		Female	–	0.57	0.58
	≥LML	Male	0.66	0.55	0.59
		Female	0.34	0.45	0.41
	Total	Male	–	0.50	0.46
		Female	–	0.50	0.54
Apollo Bay	<LML	Male	–	0.44	0.44
		Female	–	0.56	0.56
	≥LML	Male	0.73	0.59	0.49
		Female	0.27	0.41	0.51
	Total	Male	–	0.54	0.46
		Female	–	0.46	0.54
Queenscliff	<LML	Male	–	0.78	0.64
		Female	–	0.22	0.36
	≥LML	Male	0.50	0.50	0.50
		Female	0.50	0.50	0.50
	Total	Male	–	0.54	0.53
		Female	–	0.46	0.47

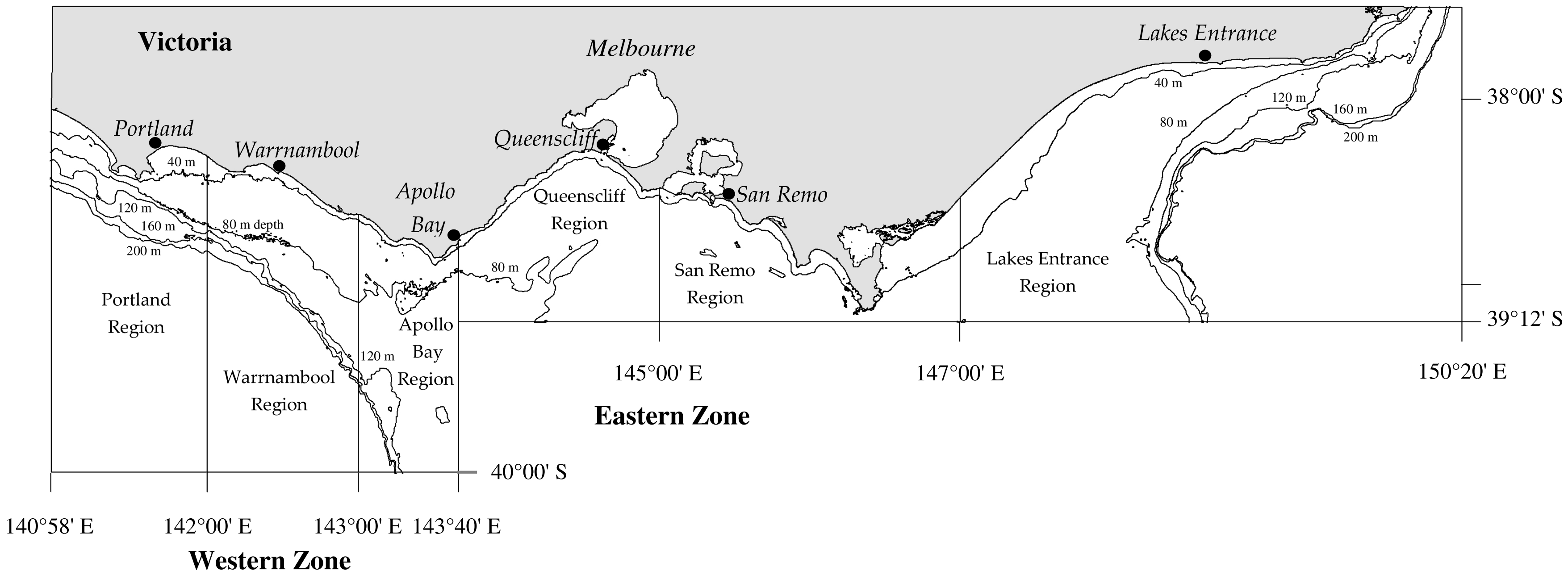


Figure 1. Western Zone and Eastern Zone in Victoria

Western Zone is divided at longitudes 142°00' E and 143°00' E into Portland Region, Warrnambool Region, and Apollo Bay Region, and Eastern Zone is divided at longitudes 145°00' E and 147°00' E into Queenscliff Region, San Remo Region and Lakes Entrance Region where each region is named after its largest fishing port.

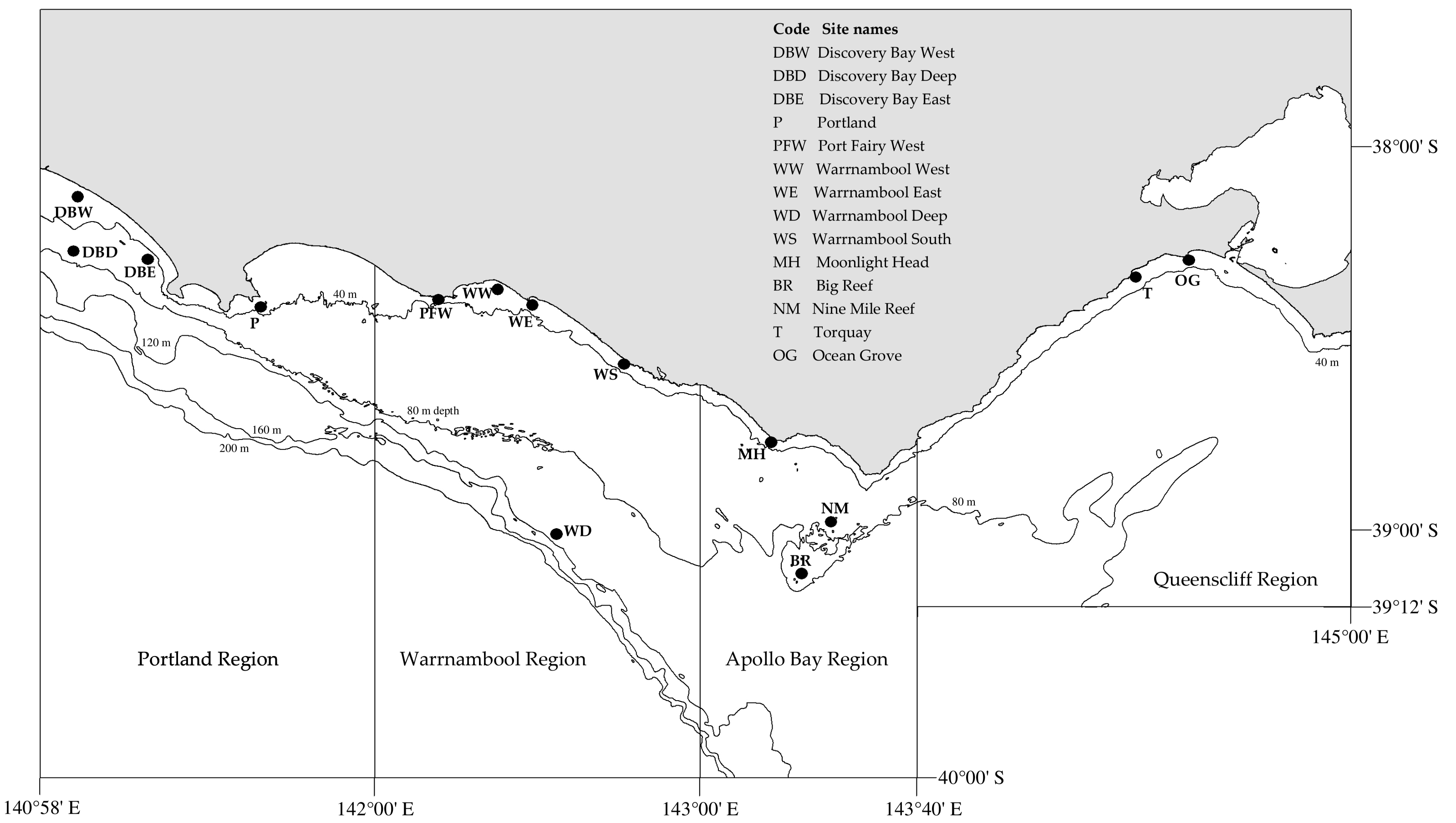


Figure 2. Positions of sites for annual fixed-site survey and the four most western regions of Victoria

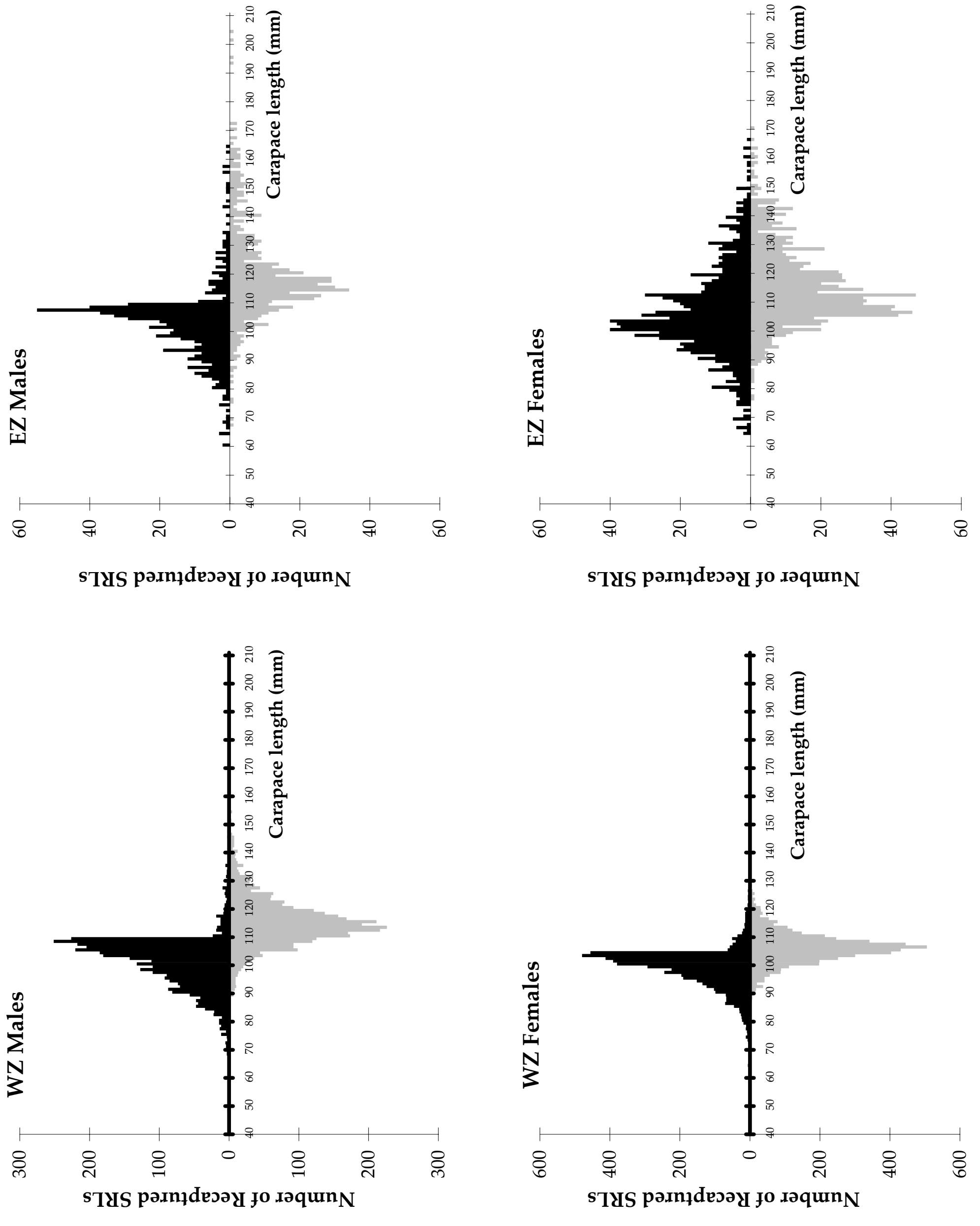


Figure 3. SRL tag length-frequency distributions at realease (above) and recapture (below) in each zone 1975–2011

SRL, southern rock lobster.

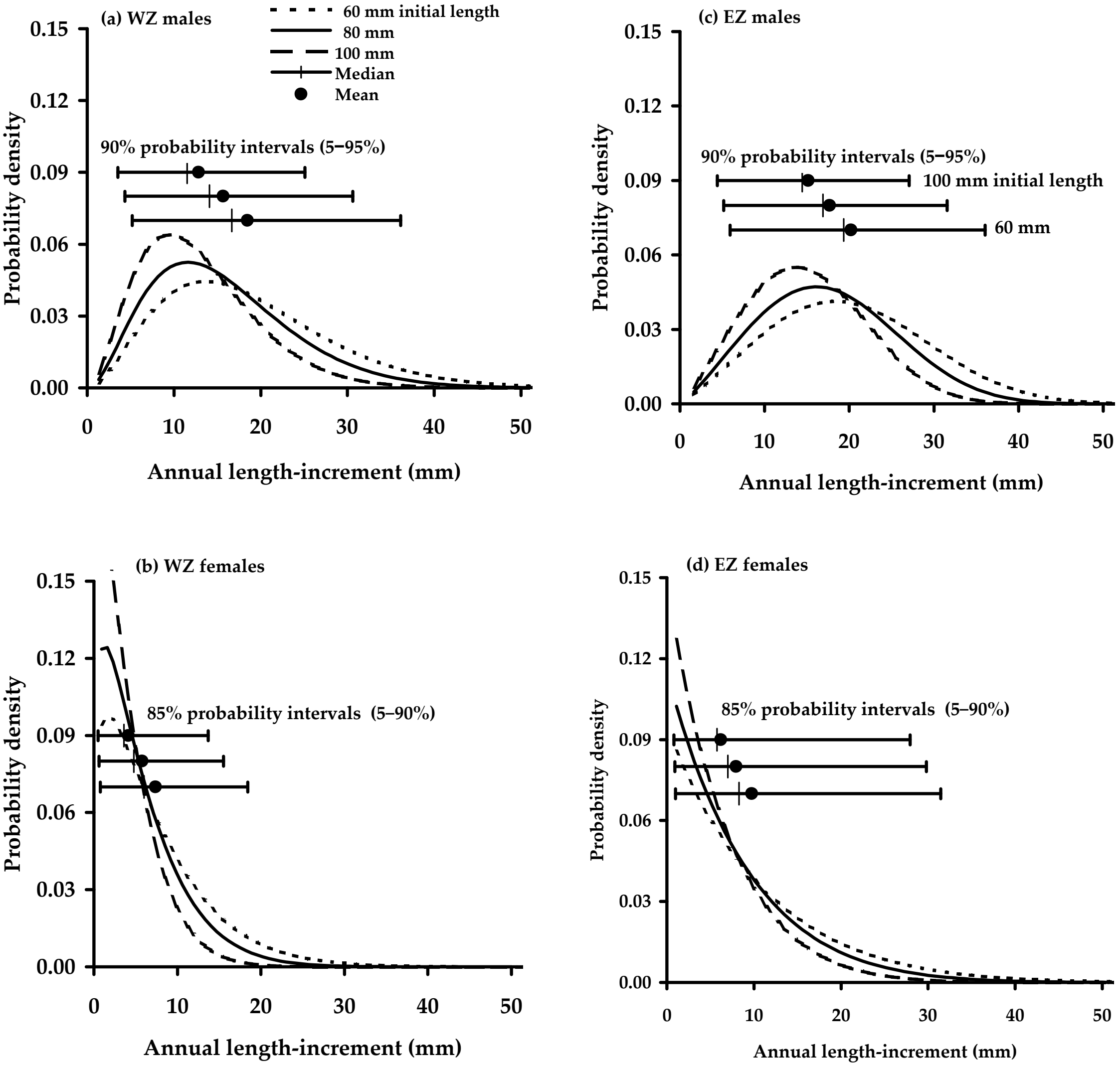


Figure 4.1.1. Annual length-increment probability density curves for each zone and each sex for all years

Mean, median and probability intervals (90% from 5% to 95% for males and 85% from 5% to 90% for females) shown with annual length-increment probability density curves for southern rock lobsters of initial lengths of 60 mm, 80 mm and 100 mm shown separately for Western Zone (WZ) males (a) and females (b) andEastern Zone (EZ) males (c) and females (d); lobster-pot selectivity-adjustment based on Richards selectivity function for Apollo Bay Escape-gap Experiment; T, minimum period at liberty for selection from available data for inclusion in analysis where T=0.50 years; all years, from 1975 –76 to 2010–11.

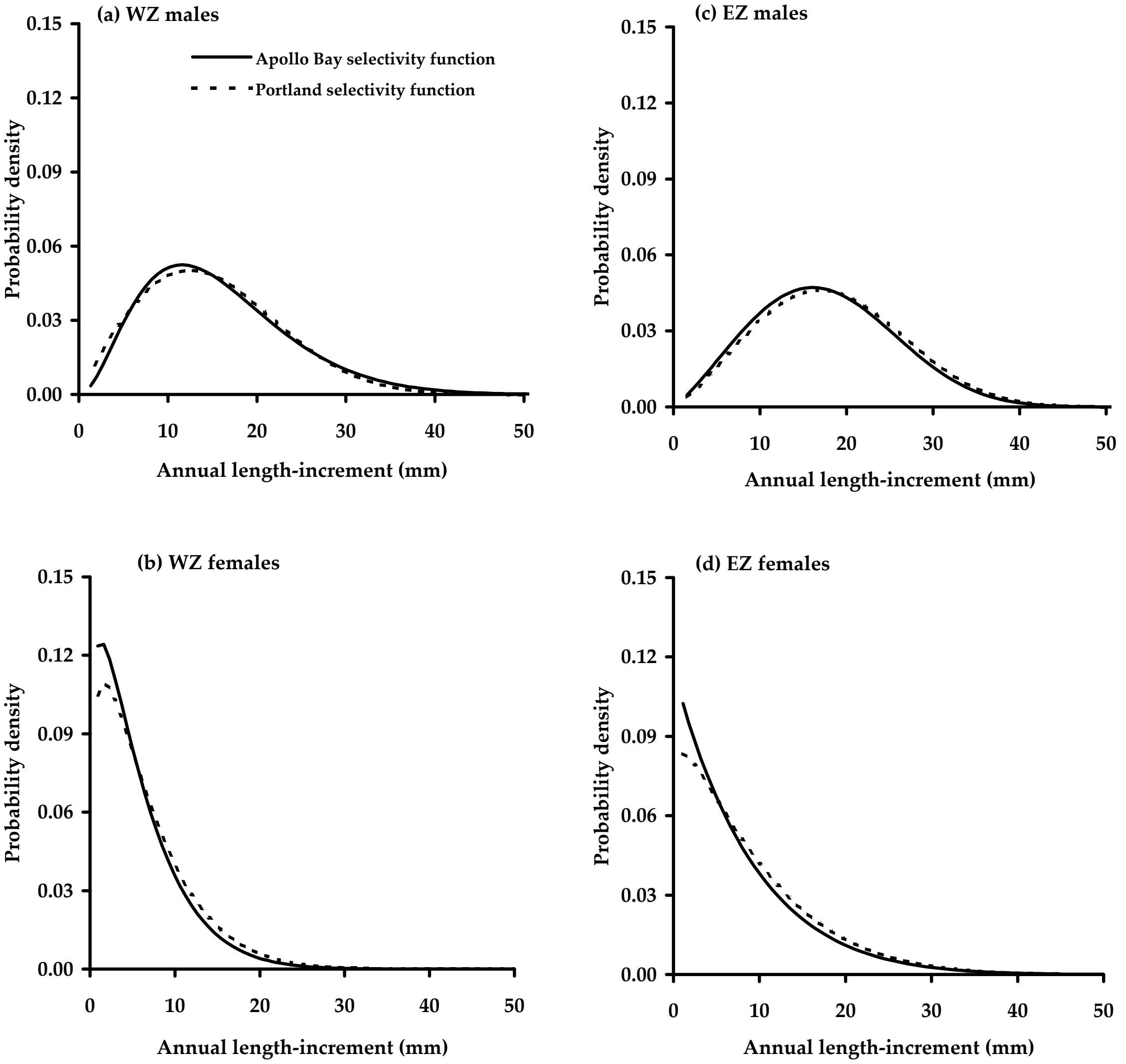


Figure 4.1.2. Sensitivity of annual length-increment pdc for 80 mm SRL to effects of selectivity function by zone and sex for all years

pdc, probability density curve; annual length-increment pdc for southern rock lobsters (SRL) of initial length 80 mm is shown separately for Western Zone (WZ) males (a) and females (b) and Eastern Zone (EZ) males (c) and females (d); lobster-pot selectivity-adjustments are based on the Richards selectivity function for Apollo Bay Escape-gap Experiment and the Richards selectivity function for Portland Escape-gap Experiment (Treble *et al* . 1998); T, minimum period at liberty for selection from available data for inclusion in analysis where T=0.50 years; all years, from 1975–76 to 2010–11.

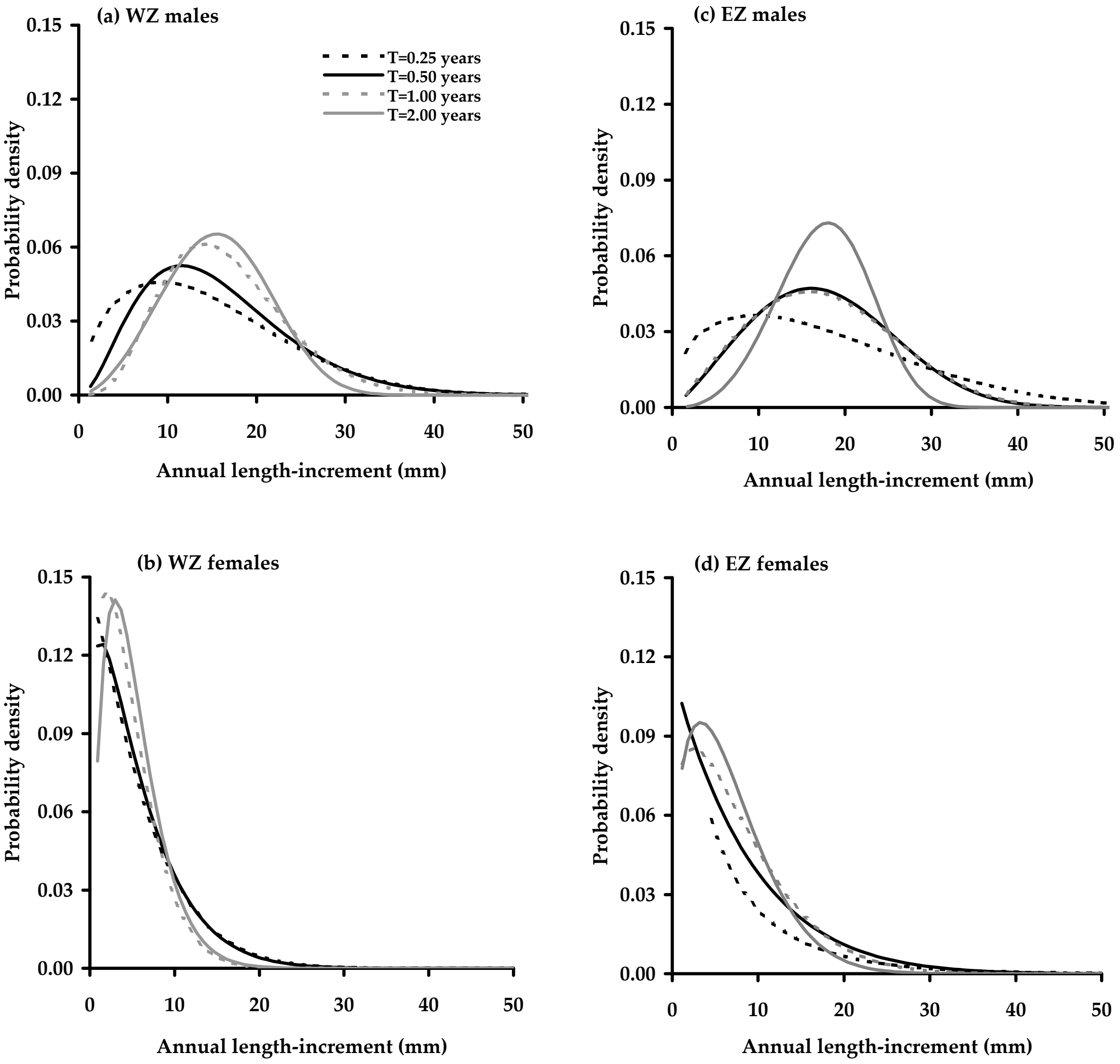


Figure 4.1.3. Sensitivity of annual length-increment pdc for 80 mm SRL to effects of *T* by zone and sex for all years

pdc, probability density curve; T, minimum period at liberty for selection from available data for inclusion in analysis; annual length-increment pdc for southern rock lobsters (SRL) of initial length 80 mm shown separately for Western Zone (WZ) males (a) and females (b) and Eastern Zone (EZ) males (c) and females (d); lobster-pot selectivity-adjustment based on Richards selectivity function for Apollo Bay Escape-gap Experiment; all years, from 1975–76 to 2010–11.

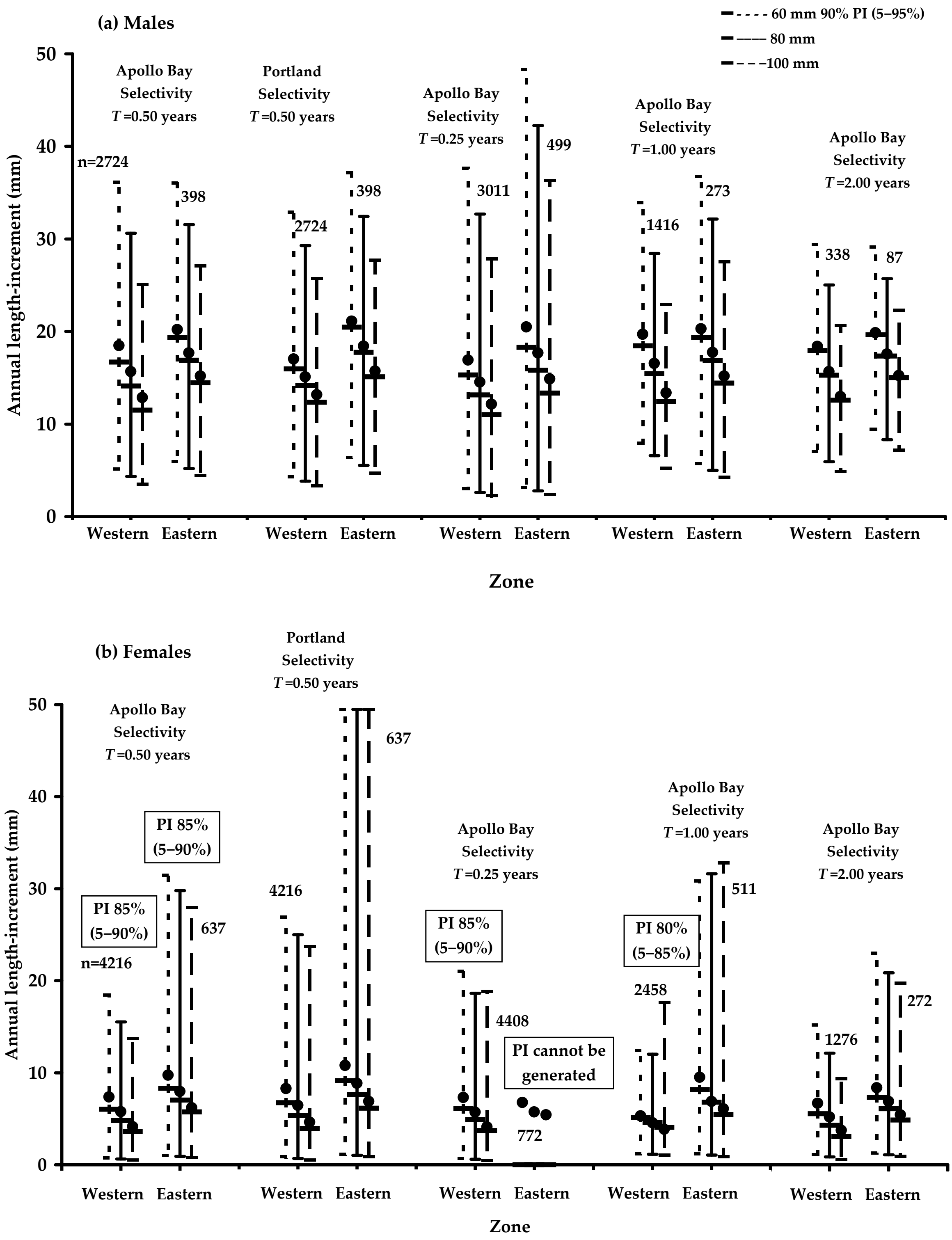


Figure 4.1.4. Sensitivity of SRL annual length-increment to effects of selectivity function and *T* by zone and sex for all years

Comparison is based on mean and median with 90% probability interval (PI) (5−95%) (exceptions in boxes on graph) for annual length-increment shown for southern rock lobsters (SRL) of initial lengths of 60 mm, 80 mm and 100 mm; n, sample size given above probability interval for each zone from 1975−76 to 2011−12 fishing years; lobster-pot selectivity-adjustments are based on the Richards selectivity function for Apollo Bay Escape-gap Experiment or the Richards selectivity function for Portland Escape-gap Experiment (Treble et al. 1998); *T*, minimum period for tagged SRL at liberty; all years, from 1975−76 to 2010−11.

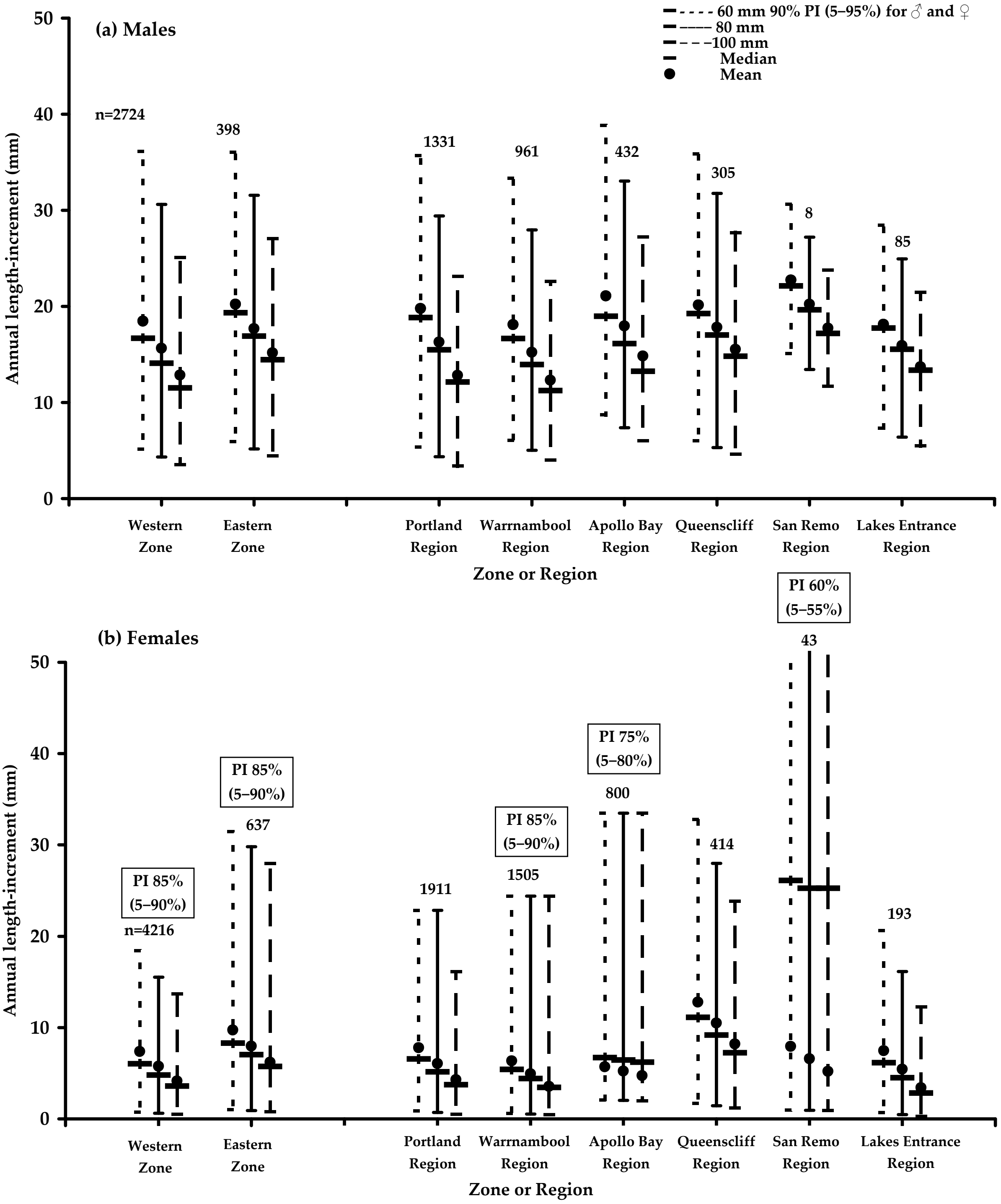


Figure 4.1.5. Comparison of SRL annual length-increment among two zones and six regions for each sex for all years

Comparison is based on mean and median with 90% probability interval (PI) (5−95%) (exceptions in boxes on graph) for annual length-increment shown for southern rock lobsters (SRL) of 60 mm, 80 mm and 100 mm initial length; n, sample size is given above probability interval for each fishing year; lobster-pot selectivity-adjustments are based on the Richards selectivity function for Apollo Bay Escape-gap Experiment; T, minimum period at liberty for selection from available data for inclusion in analysis where T=0.50 years; all years, from 1975−76 to 2010−11.

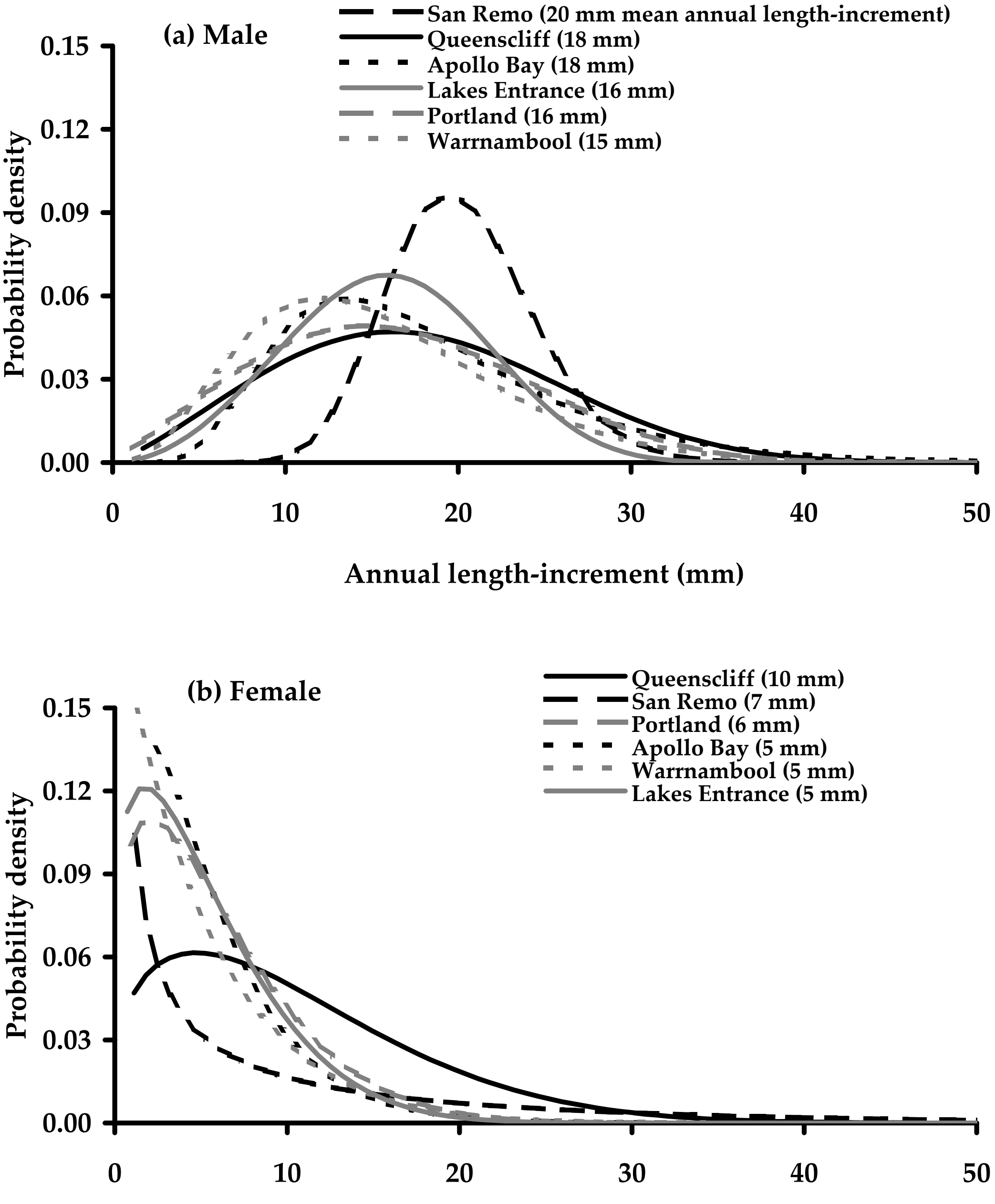


Figure 4.1.6. Annual length-increment pdc for 80 mm SRL in each region for all years

Pdc, probability density curve; SRL, southern rock lobsters; regions in legend are listed from highest to lowest mean annual length-increment for males (a) and females (b); lobster-pot selectivity-adjustments are based on the Richards selectivity function for Apollo Bay Escape-gap Experiment; T, minimum period at liberty for selection from available data for inclusion in analysis where T=0.50 years; all years, from 1975−76 to 2010−11.

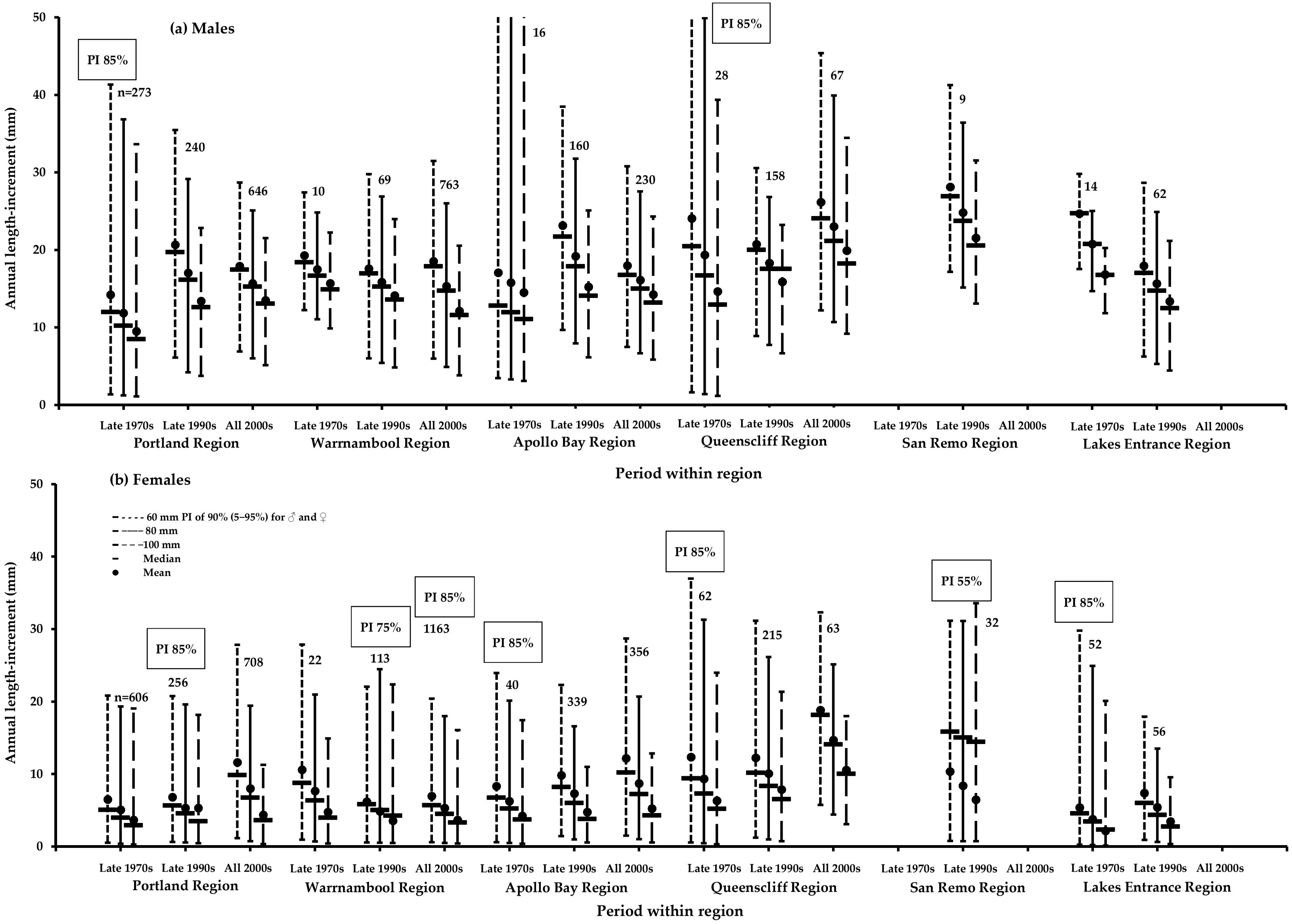


Figure 4.2.1. Comparison of SRL annual length-increment among three periods within six regions from 1975−76 to 2010−11

Comparison is based on mean and median with 90% probability interval (PI) (5−95%) (exceptions in boxes on graphs) of annual length-increment shown for southern rock lobsters (SRL) of 60 mm, 80 mm and 100 mm of initial lengths; n, sample size for each site is given above probability interval shown for each period in each region; Late 1970s, from 1975−76 to 1978−79; Late 1990s, from 1994−95 to 1998−99; and All 2000s, from 2001−02 to 2010−11; lobster-pot selectivity-adjustment based on Richards selectivity function for Apollo Bay Escape-gap Experiment; T, minimum period at liberty for selection from available data for inclusion in analysis is standard at 0.50 years (reduced to 0.25 years for each of males and females for Late 1990s in San Remo Region).

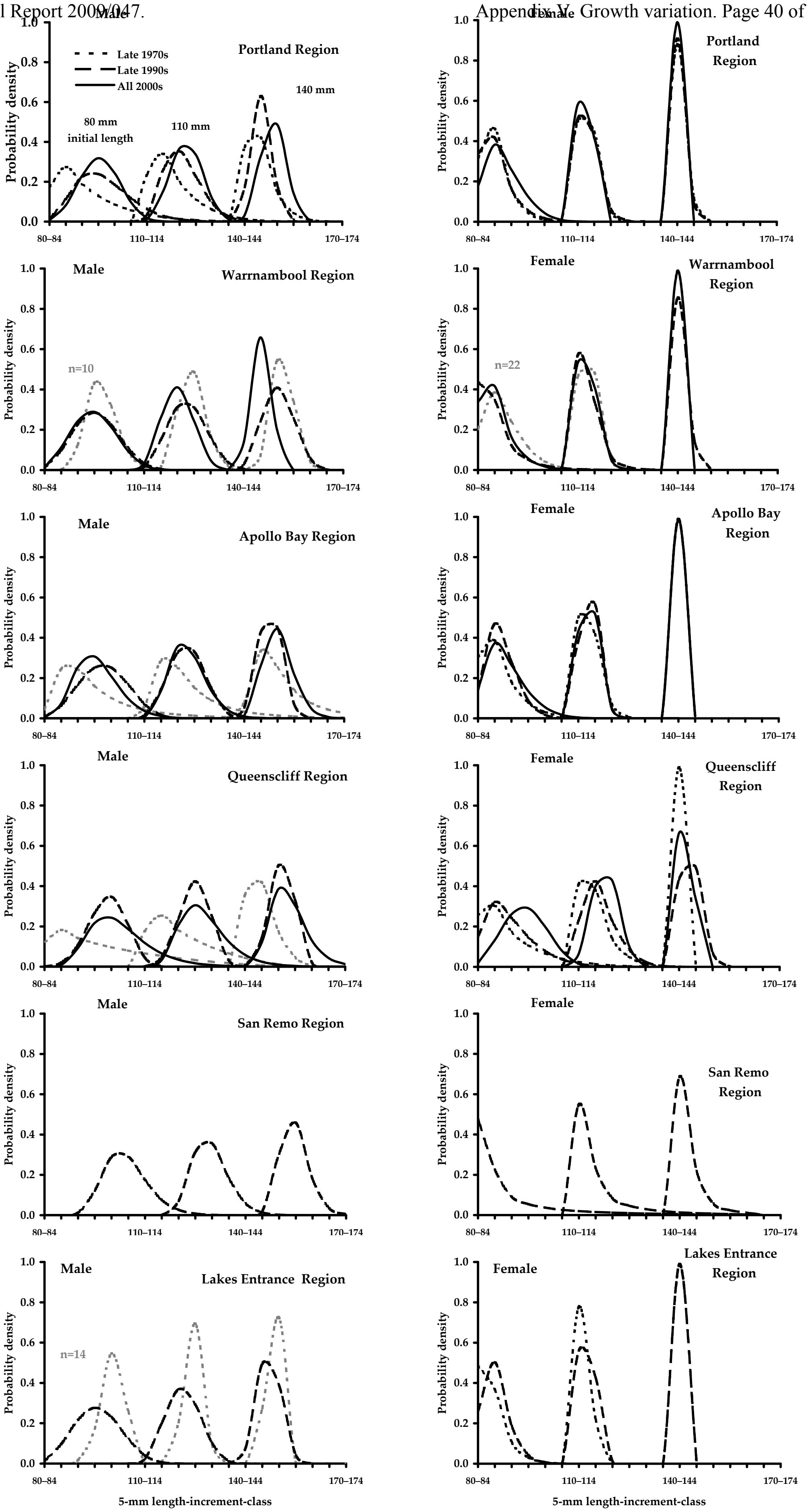


Figure 4.2.2. Annual length increment pdc for 80, 110 and 140 mm SRL by sex and period in each region

pdc, probability density curve; SRL, southern rock lobster; T, minimum period at liberty for selection from available data for inclusion in analysis is standard at 0.50 years (reduced to 0.25 years for each of males and females for Late 1990s in San Remo Region); lobster-pot selectivity-adjustment based on Richards selectivity function for Apollo Bay Escape-gap Experiment.

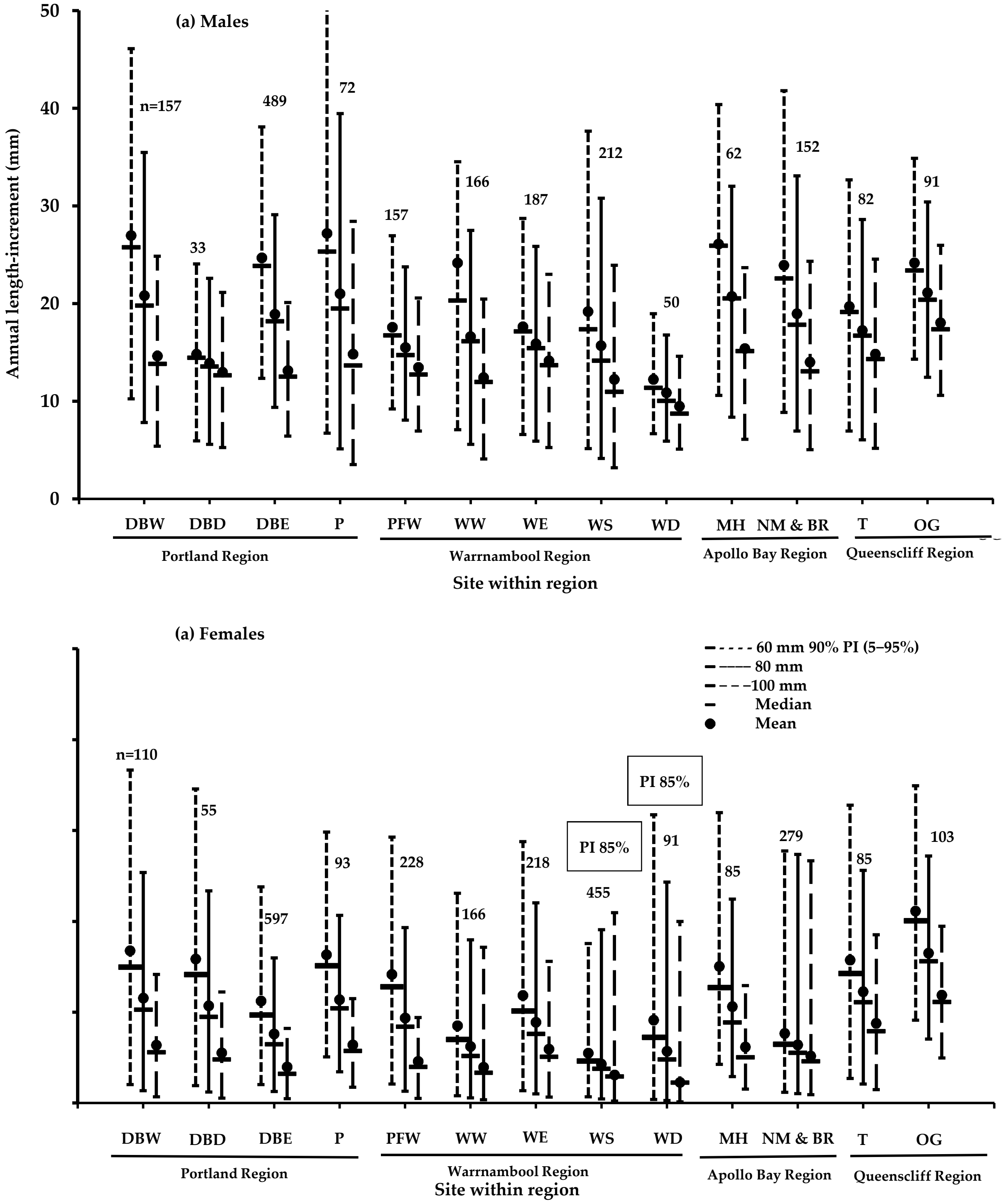
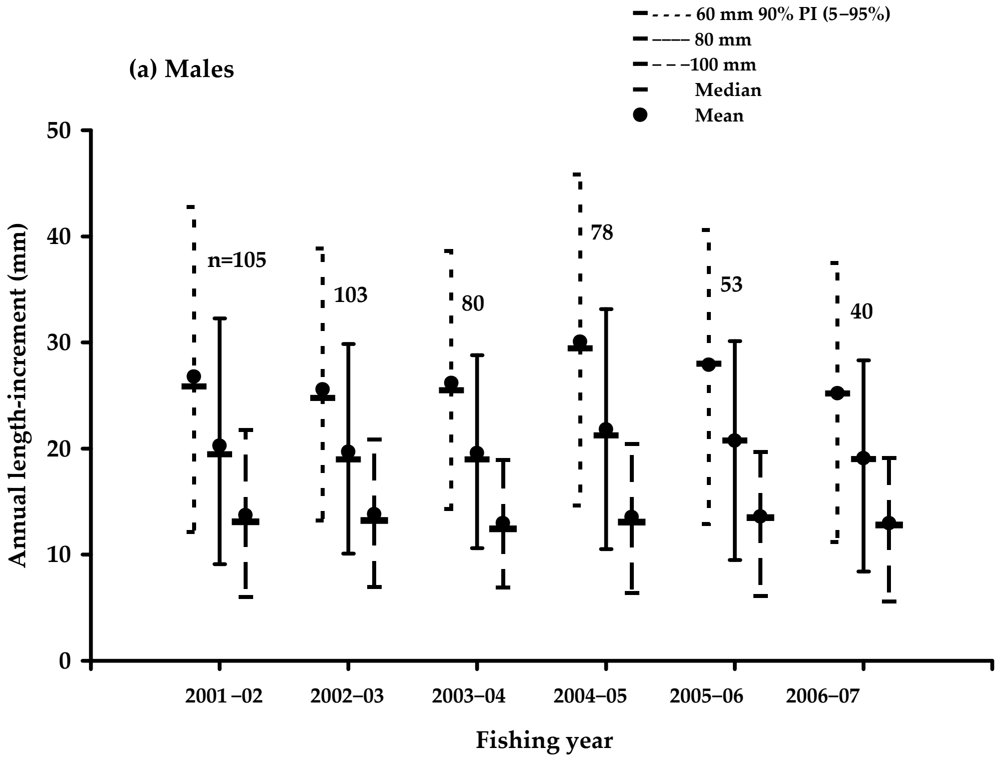


Figure 4.3.1. Comparison of SRL annual length-increment among sites by sex for period of fixed-site survey tagging

Comparison is based on mean and median with 90% prediction interval (PI) of annual length-increment for southern rock lobsters (SRL) of 60 mm, 80 mm and 100 mm initial lengths; n, sample size for each fishing year given above prediction interval for fixed site; period of fixed-site survey tagging is from 1995−96 to 2010−11 in Eastern Zone and from 2001−02 to 2010−11 in Western Zone; lobster-pot selectivity-adjustment based on Richards selectivity function for Apollo Bay Escape-gap Experiment; *T*=0.50 years.

(a) Males



(b) Females

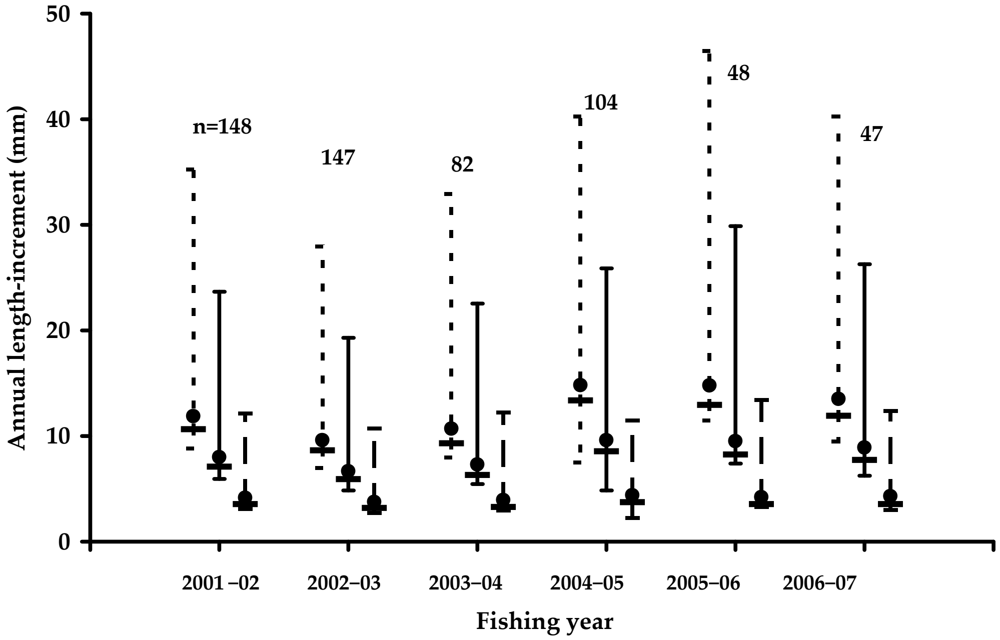
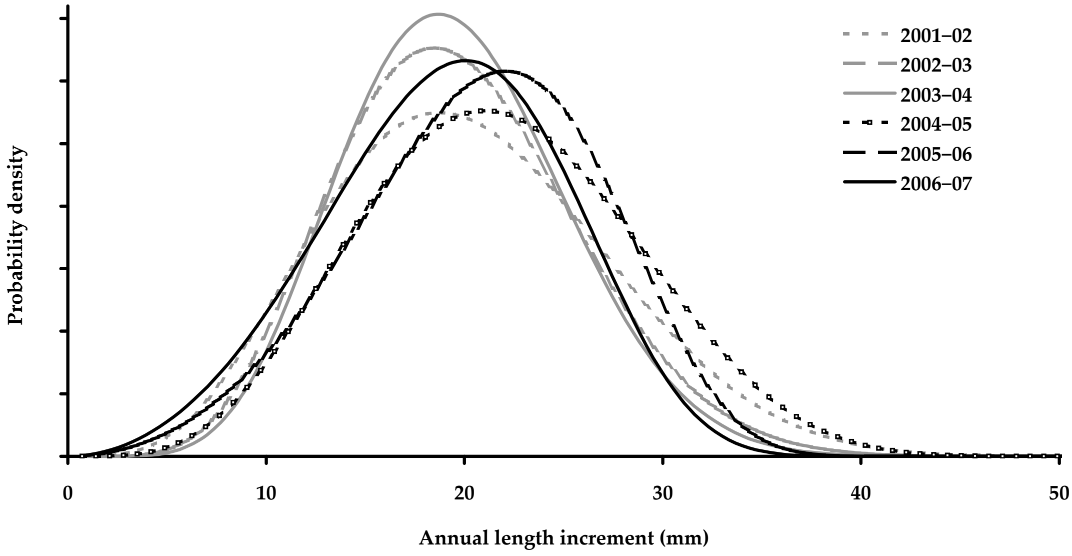
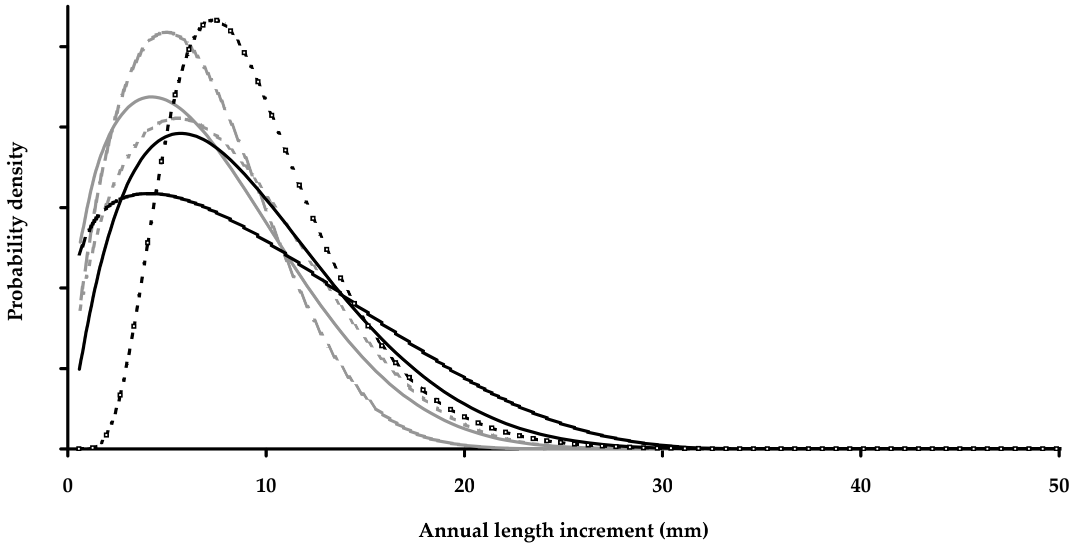


Figure 4.4.1. Comparison of SRL annual length-increment among six fishing years at Site DBE by sex

Comparison is based on mean and median with 90% prediction interval (PI) of annual length-increment for southern rock lobsters (SRL) of 60 mm, 80 mm and 100 mm initial lengths; n, sample size for each fishing year given above prediction interval for each fishing year from 2001–02 to 2006–07 fishing years; DBE, Discovery Bay East fixed site (Portland Region); lobster-pot selectivity-adjustment based on Richards selectivity function for Apollo Bay Escape-gap Experiment; *T*=0.50 years.



(a) Males



(b) Females

Figure 4.4.2. Comparison of SRL annual length-increment pdcs for 80 mm initial length among six fishing years at Site DBE by sex

SRL, southern rock lobster; pdc, probability density curve; DBE, Discovery Bay East fixed site (Portland Region); six fishing years are from 2001–02 to 2006–07.

The Performance of a Management Procedure for Rock Lobsters, *Jasus edwardsii,* off Western Victoria, Australia in the face of Non-stationary Dynamics

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Abstract

The biomass of rock lobster, *Jasus edwardsii*, has declined across southern Australia, including western Victoria. Environmentally-driven changes in recruitment and high fishing mortality are likely the major causes for this decline although trends in natural mortality, catchability and growth cannot be excluded. Management Strategy Evaluation is used to evaluate a management procedure which has been proposed for rock lobsters off Victoria. This management procedure aims to recover the resource to a target level of exploitable biomass and to maintain egg production above a limit reference point. The management procedure is evaluated in terms of i) catches, ii) the risk of not achieving conservation goals, and iii) the bias of estimates from the stock assessment given scenarios in which natural mortality, catchability, growth and recruitment are exhibiting future trends. In general, the exploitable biomass is driven towards the target level as expected. Changes over time in natural mortality and growth are relatively inconsequential for the performance of the management procedure, and the impact of changes over time in growth can be mitigated through ongoing tagging programs. In contrast, trends in catchability and recruitment will lead to management goals not being satisfied, with trends in catchability the most problematic because such trends lead to bias in stock assessment outcomes even if data sources which provide unbiased information on abundance are available for assessment purposes.

Keywords: Australia, environment, rock lobster, management strategy evaluation, stock assessment

Introduction

Crustacean fisheries are some of the world's most valuable and profitable. Management procedures (combinations of data collection schemes, assessment methods and harvest control (or decision) rules, HCRs) are increasingly being used to specify management actions (e.g. Total Allowable Commercial Catches, TACCs) for commercially-exploited rock lobster and crab populations (e.g. DPI, 2009; NPFMC, 2010; Punt *et al.*, 2012). Some of these management procedures (e.g. Starr *et al.*, 1997; Johnston and Butterworth, 2005; Punt *et al.*, 2012) were evaluated using Monte Carlo simulation (i.e. using the Management Strategy Evaluation, MSE, approach; Butterworth, 2007) prior to their first application. However, the vast bulk of management procedures (particularly their HCR components) were developed *in committio* rather than *in silico*, with the consequence that while they may appear sensible *a priori*, they need not be fully specified, and their likely performance in terms of achieving management goals remains unknown.

Management procedures can be divided into those which are 'empirical' and those which are 'model-based'. 'Empirical' management procedures specify management actions directly from data collected from the fishery without using those data to fit a population dynamics model (e.g., De Oliveira and Butterwornh, 2004). It is generally believed that 'empirical' management procedures are more responsive to rapid changes in monitoring data, but at the expense of leading to more variation in management actions and hence catches (Butterworth and Punt, 1999; Cox and Kronlund, 2008; Punt *et al.*, 2012). It is possible to simulate the use of an 'empirical' management procedure many thousands of times on a desktop computer in a few minutes. However, it can take days (or weeks) to simulate a typical 'model-based' management procedure even on a fast desktop computer, which is one reason that few studies have evaluated model-based management procedures. Nevertheless, model-based management procedures are often desired by management agencies because they can produce estimates of, for example, stock size relative to target and limit reference points, as well as the rate of recovery for 'overfished' populations, which may be needed for reporting purposes and to satisfy legislative mandates.

The fishery for rock lobster, *Jasus edwardsii*, off Victoria Australia is that state's 2nd most valuable (average first-sale revenues of a mean annual AU$14.5 million from 2001/02 to 2007/08 or 27% of the first-sale revenue of all wild-caught marine fishery resources off Victoria[1]). The fishery is divided into Eastern and Western Zones

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[1] http://new.dpi.vic.gov.au/fisheries/commercial-fishing/commercial-fish-production-2010

(Fig. 1), although the vast bulk (87% over the 10-year period from the 2001–02 (16 November − 15 September) to the 2010–11 fishing year (Walker *et al.* 2012)) of the commercial catch is taken from the Western Zone. The fishery is managed using a variety of effort controls (e.g. limits on licenses and pot numbers; escape gaps, etc.) and Total Allowable Commercial Catches (TACCs) since the 2001–02 licensing year (i.e., 1 April 2001 – 31 March 2002). The TACC for the Western Zone increased from 320t in 2001/02 to 450t in 2002/03, but has declined substantially in recent years (e.g. to 240t in 2009/10) owing to poor stock status (Fig. 2).

Declining abundance of rock lobsters, inferred either from the results of stock assessments or from trends in puerulus and catch-rates, has been documented throughout the entire range of *J. edwardsii* off southern Australia (Linnane *et al*., 2010). While the reasons for the decline clearly include high exploitation rates (>40% in many years in some areas), simultaneous patterns of decline across the Australian range of the species indicate that possible large-scale environmental influences may be playing a role (Linnane *et al*., 2010).

There are several possible mechanisms by which environmental change can impact the dynamics of lobsters. For example, larval survival and growth is highly temperature dependent (Bermudes and Ritar, 2008, Thomas et. al., 2000) while recruitment is highly dependent on changing ocean currents (Ridgway, 2007) due to the lengthy pelagic phase. Evidence from tagging studies in South Australia indicates that growth rates of both male and female lobsters have decreased in recent seasons compared to estimates from the mid 1990's (Linnane *et al.,* 2011a,b), and it has been suggested that this may be linked to increases in upwelling intensity where extreme cold-water events impact local populations (Linnane *et al*., 2010). Lobster growth rates in other areas are highly correlated with water temperature, and may increase with warming waters (Pecl et. al., 2009). Lobsters become more active as water temperatures increase, which could lead to an increase in fishery catchability over time (Ziegler et. al., 2003, 2004). Finally, shifts in ecosystem composition might influence natural mortality through food availability and predation (Pecl et. al., 2009).

The management plan for the Victorian rock lobster fishery was modified recently (DPI, 2009), and the approach used to provide scientific recommendations for TACCs includes a model-based HCR (see "management procedure" below for further details). A key feature of this approach is a set of steps based on assessing whether stocks are above or below reference points and determining the levels of catch that are predicted to allow recovery to the target level given an agreed time-frame. Projections for rock lobsters off Victoria are based on a stock assessment model (Hobday and Punt, 2001, 2009; Hobday *et al*., 2005) and assumptions that parameters such as average recruitment and growth are constant into the future. The possibility of large-scale environmental forcing means that the assumptions underlying these projections may be violated, with consequences for the ability of this management procedure to satisfy the management goals outlined in DPI (2009).

This paper uses Management Strategy Evaluation, MSE, to evaluate a management procedure which can be inferred from DPI (2009) for Victoria's Western Zone rock lobster fishery under the ideal situation in which the assumptions made when forecasting abundance are correct and in which key production- and fishery-related parameters (growth, natural mortality, recruitment and catchability) exhibit future trends over time.

Material and methods

Overview

MSE involves simulating the entire management cycle, including data collection, assessment, application of HCRs, implementation of regulations, and the consequences of removals on the population dynamics. It has been applied widely to evaluate management procedures for single-species fisheries (e.g., Johnston and Butterworth, 2005), for multi-species fisheries (e.g., De Oliveira and Butterworth, 2004), and to achieve ecosystem objectives (e.g., Sainsbury *et al*., 2000). MSE has previously been applied to rock lobsters off Victoria (Punt and Hobday, 2009) to evaluate the impact of spatial structure on the performance of the HCR specified in an earlier management plan (Anon., 2003). That HCR, which did not have explicit rebuilding requirements, was replaced by the HCR specified in DPI (2009).

The MSE in this paper involves an operating model, which specifies the "true" dynamics of the system being managed, including hypotheses for future changes over time in some of the biological and fishery parameters, a management procedure, and specifications for future data collection. The MSE is based on the assumption that TACCs are taken exactly so that the impact of non-stationary parameters on the ability to achieve management goals and on the ability of the stock assessment to provide reliable estimates can be determined without the results being confounded by implementation errors. For the same reason, the management procedure is based on the same population dynamics model as the operating model and some of the parameters of that model (e.g. the proportion mature by length and average natural mortality) are assumed known.

The following sections outline the operating model, the management procedure, and the scenarios used to evaluate how different forms of non-stationarity in parameters could impact the ability to achieve management goals. Finally, the performance measures used to summarize management and estimation performance are outlined.

The operating model

The operating model is sex- and size-structured, with an annual time-step, and treats the entire Western Zone as a single homogeneous area, i.e.:

$$\underline{N}_{y+1,s} = \mathbf{X}_{y,s}\mathbf{S}_{y,s}\underline{N}_{y,s} + \underline{R}_{y+1,s} \tag{1}$$

where $\underline{N}_{y,s}$ is the number of animals by sex and size-class at the start of year *y*, $\mathbf{X}_{y,s}$ is the sex-specific size-transition matrix for year *y* (which determines the proportion of animals which grow from one size-class to another given they survived), $\mathbf{S}_{y,s}$ is the matrix of survival probabilities for sex *s* during year *y*, and $\underline{R}_{y,s}$ is the recruitment (by size-class) for sex *s* during year *y* (assumed 50:50 male:female for consistency with the stock assessment). The survival matrix is diagonal with entries:

$$S_{y,s,i} = e^{-M_y}(1-\tilde{S}_{s,i}F_y) \tag{2}$$

where M_y is the rate of natural mortality during year *y*, $\tilde{S}_{s,i}$ is the vulnerability of animals of sex *s* in size-class *i* to fishing (logistic above the legal minimum size of 110 mm (males) and 105mm (females), and zero below this size) and F_y is the fully-vulnerable exploitation rate during year *y* (combining the effects of commercial and recreational harvests, which are assumed to have the same vulnerability patterns).

The assumption that the entire Western Zone is homogenous with respect to population structure and biological parameters is likely to be violated to some extent because it is known that growth and maturity differ across this Zone (Punt *et al*., 2006a,b), and model-selection methods support conducting stock assessments for spatial sub-divisions of the Western Zone (Hobday and Punt, 2009). However, this study is based on the homogeneity assumption because while work is progressing to move to an assessment which divides the Western Zone into three sectors, the assessment on which management advice is currently based remains one in which the whole Zone is assessed as a single unit (see, for example Walker *et al*., 2012). Moreover, ignoring spatial structure should help to make evident the impact of changes in biological and fishery parameters in contrast to bias caused by mis-specification of spatial structure.

The entries for the size-transition matrices by sex, $\mathbf{X}_y$, for years up to 2010 are obtained by applying the method of Troynikov (1998) to tagging data for rock lobsters in the Western Zone, and weight-at-length is set as in Hobday and Punt (2001). Natural mortality for the years up to 2010 is set to 0.1yr^{-1}, the value typically assumed in assessments of *J. edwardsii*. The values for the remaining parameters (vulnerability and recruitment) are estimated by fitting the operating model to data on commercial catch-rates, commercial length-frequency data by sex , and the numbers caught annually. Vulnerability for females is assumed to be 68% of that for males to account for the closed season for berried females (Hobday and Punt, 2001). Catches (and catch-rates) are available from 1951, but the operating model starts in 1931 so that the size-structure is not at equilibrium in 1951. The uncertainty associated with the estimates for the parameters of the operating model is quantified by conducting a parametric bootstrap in which each pseudo data set is generated by adding simulated observation error to model predictions based on the assumed sampling distributions and the estimates for the residual variances.

Future recruitment is generated by sampling from past recruitments (allowing for a trend in future recruitment where relevant). The analyses are not based on simulating future recruitment from a stock-recruitment relationship *inter alia* because it is unlikely given the long larval duration for rock lobsters that recruitment to the Victoria's Western Zone is produced by spawning in this area (Bruce *et al*., 2007).

The data available for use in future assessments are the data available at present plus simulated future catch-rates, catches-in-numbers, and catch length-frequencies by sex. The simulated catch-rates, I_y, are assumed to be log-normally distributed, with a catchability coefficient which may change in the future, i.e.:

$$I_y = qe^{\psi(y-2010)}B_y\, e^{\eta_y-\sigma_I^2/2} \qquad \eta_y \sim N(0;\sigma_I^2) \tag{3}$$

where *q* is the base level of catchability, ψ determines the rate at which catchability increases over time, B_y is the exploitable biomass in the middle of year *y*, and σ_I determines the extent of variation in catch-rates (set to

0.103 based on the fit of the operating model to the actual data). The catch-in-numbers is assumed to be log-normally distributed about the true catches-in-numbers with a CV of 0.082 (again selected from the fit of the operating model to the actual data). The future length-frequency data by sex are multinomial samples from the operating model-predicted catch-length-frequencies. The effective sample size for the length-frequency data is 26 based on the approach of McAllister and Ianelli (1997).

The final source of data relates to the growth. For those scenarios in which it is assumed that the size-transition is updated regularly, the assessment is provided with a size-transition matrix which is an average over the most recent five years, i.e. $\frac{1}{5}\sum \mathbf{X}_y$. New size-transition matrices are assumed to become available in 2015, 2020, etc. Rather than attempting to simulate the process of tagging and recapturing lobsters, followed by the application of the model of Troynikov (1998), the analyses assume that $\frac{1}{5}\sum \mathbf{X}_y$ is estimated without error. This provides the maximum amount of possible information on future changes in growth.

The management procedure

The management procedure consists of two components, a stock assessment and a HCR. The stock assessment matches that currently used to provide management advice and structurally matches the operating model. The stock assessment may allow for time-varying growth, but in common with the current assessment assumes that natural mortality and catchability are time-invariant, and that the prior for recruitment is log-normal about a time-invariant mean. Given concerns regarding non-stationarity, the catch-rate and catch-in-numbers data are re-weighted in the likelihood such that the most recent year of data is weighted twice as heavily as data from ten years earlier. The weights for intermediate years are linearly increasing. Data from 10 years ago and earlier are equally weighted.

The main outcomes of the stock assessment are the time-trajectories of exploitable biomass, egg production, and recruitment as well as projections of these quantities and future levels of catch. For the projections, growth is assumed to be time-invariant (with the size-transition matrix set to the most-recent estimate), and recruitment from year *y*last+1 is set to the average values over years *y*last-3 to *y*last-7 where *y*last is the most-recent year included in the assessment. The most recent three recruitment estimates are ignored and also not used when determining average future recruitment because these estimates are poorly determined by the data. The use of a moving average recruitment over time when projecting means that trends in recruitment are reflected (to some extent) in projections.

The HCR used to convert the results of the stock assessment into a recommended TACC for the next fishing season (Fig. 3) involves assessing whether the stock is below the limit reference point, between the limit and the target reference points, or above the target level reference point, and applying different decision rules for each of these three cases[2].

- A "recovery plan" is implemented if the stock is assessed to be below the limit reference point (20% of the egg production in 1951, $0.2\mathrm{EP}_{1951}$), and TACCs are set so that recovery to the limit reference point occurs in two years (Fig. 3a). A new recovery plan is implemented (with the aim for recovery over another two years) if recovery to the limit reference point does not occur within two years. If it is necessary to extend the time to recovery because a previous attempt failed, the TACC may not increase when the new recovery plan is implemented (the TACCs during the recovery period are constrained by TACC**). The value of TACC** is ignored (essentially set to ∞) prior to implementing a recovery plan for the first time and once recovery to the limit reference point occurs.
- A "rebuilding plan" is implemented if the stock is assessed to be above or equal to the limit reference point, but below the target reference point (40% of the exploitable biomass in 1951, $0.4B_{1951}$), and TACCs are set so that rebuilding should occur within 10 years and ideally within 8 years. If a new rebuilding plan is implemented, the TACC is set so that rebuilding to the target reference point is predicted to occur in 8 years (subject to the constraint that it cannot exceed the TACC for the previous year and that TACCs cannot be reduced more than 50%; Fig. 3b). Following the first year of the rebuilding plan, the TACC is set yearly after the annual cycle of data gathering from the operating model, stock assessment estimation, and projection modelling during the next seven years of the rebuilding plan (down by 50% or up by 10%; i.e., $\delta=0.5$, $\lambda=1.1$) so that the predicted time to rebuilding to $0.4B_{1951}$ continues to be 8 years after the rebuilding plan started. If the stock has not rebuilt after 8 years under the rebuilding plan, the TACC is set with the aim of rebuilding to the target in a further two years and the TACC for the 10th year of rebuilding plan (if recovery has not occurred by then) is set to the TACC for the 9th year (to avoid marked changes in TACC during the last year of the rebuilding

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[2] For ease of presentation, setting TACCs to allow the biomass to increase to the limit reference point is referred to as a recovery plan; setting TACCs to increase to the target reference point is referred to as rebuilding plan.

plan). If rebuilding does not occur within the 10-year time-frame, a new rebuilding plan is started, but the TACC during the next 10 years cannot exceed the TACC for the last year of the failed rebuilding plan (i.e., TACC* in Fig. 3b is set to the TACC for the last year of the failed rebuilding plan). The value of TACC* is ignored (essentially set to ∞) prior to implementing a rebuilding plan for the first time and once rebuilding to the target reference point occurs.

- The TACC is set so that the exploitable biomass is predicted to equal to the $0.4B_{1951}$ in a further 5 years when the exploitable biomass is assessed to be currently above this level (Fig. 3a). The TACC can be increased by 10% or reduced by 50% given this goal, but is constrained not to exceed 500t.

Scenarios and performance measures

The scenarios consider the impact of factors related to changes in growth, natural mortality, recruitment, and catchability, as well as the impact of the average level of future recruitment. Each scenario is based on 100 simulations (one simulation for each bootstrap replicate parameter vector) of a 40-year projection period (2011−2050). The changes of over time are implemented as follows:

1. Catchability. Either constant or changes exponentially over time (Eqn 3) so that it doubles or halves in 20 years (i.e. ψ =0, 0.034657, −0.034657).
2. Natural mortality. Either constant or linear change so that in 40 years, M_{2050} would be either the same as in 2010, 0.15yr^{-1} or 0.05yr^{-1}, i.e.:
$$M_y = 0.1 + (M_{2050} - 0.1)\frac{y-2010}{40} \tag{4}$$
3. Growth. Time trends in growth are implemented by changing the probability of an animal at the minimum legal size (MLS) staying in their current size-class, i.e.: denoting the size-class corresponding to the MLS as *I*, time-varying growth is implemented using:
$$X_{I,I} = X_{I,I}^{1+x_t} \tag{5}$$
where *x* remains zero or changes linearly from 0 in 2010 to either 0.5 or −0.5 in 2050. Given values for $X_{I,I}$ the remaining entries of the size-transition matrix are rescaled so that each column sums to 1.
4. Recruitment. The scenarios consider (a) no change, (b) a linear increase in expected recruitment so that by 2050 expected recruitment is 50% larger than that projected for 2011 (c) a linear decrease in expected recruitment so that by 2050 expected recruitment is 50% smaller than that projected for 2011. This is implemented when sampling future recruitment by multiplying each selected recruitment by a scalar which changes in the same way as the assumed trend in recruitment

Two levels of average future recruitment are considered: (a) 2003−07 and (b) 1998−2007 (referred to as recruitment cases I and II). The former range is that currently used for actual assessment purposes and reflects a low value, and the latter reflects an average level of recruitment closer to the long-term average (Fig. 4). Note that the average recruitment in each future year depends on the recruitment case, but still changes linearly over time for the scenarios in which recruitment changes over time.

Given three levels for how catchability, natural mortality, growth and average recruitment might change in the future, two levels of average future recruitment, and whether or not future growth data become available leads to 324 possible simulation trials. This many trials would be extremely voluminous to report on. Therefore, results are shown for each level of average recruitment for a base line trial in which no changes occur (and hence the assessment is correct "on average") (2 trials) and for trials with changes in each factor in turn (16 trials) and for trials in which all biological factors are optimistic (i.e., faster growth, lower natural mortality, and increasing recruitment) and are pessimistic (i.e., slower growth, higher natural mortality, and decreasing recruitment) (4 trials) for a total of 22 trials.

The performance measures are the medians and 90% intervals (over simulations) for the average catch over the first 10 years of the projection period and the entire 40-year projection period, the probabilities that the stock is above 20% of the 1951 exploitable biomass (probabilities are not reported for 20% of 1951 egg production because this is always high) and the target reference point of 40% of the 1951 exploitable biomass, the year in which recovery to 40% of the 1951 exploitable biomass first occurs, the number of years (out of 40) that the stock is above 20% and 40% of the 1951 exploitable biomass, and a measure of the inter-annual variation in catches, the AAV:

$$AAV = \frac{\sum \left| TACC_{y+1} - TACC_y \right|}{\sum TACC_y} \tag{5}$$

The above statistics quantify the 'management performance' of the management procedure. Distributions of relative error for the estimates of exploitable biomass and recruitment are used to quantify the impact of violations of the assumption of time-invariant parameters on the estimation performance of the stock assessment (and to better understand why the management procedure behaves as it does).

Results

Reference case scenario

The reference case scenario represents an 'ideal' in which all of the biological and fishery parameters are stationary, as assumed by the stock assessment (i.e. natural mortality, growth and catchability are constant over time and recruitment is drawn at random from a reference period). The exploitable biomass is close to half of the target reference point of 40% of the 1951 level at the start of the projection period (vertical lines in Figs 5a,b). Recovery to the target level occurs fairly rapidly (and as expected given the underlying objectives of the management procedure; the median years of recovery are 2016 and 2015 respectively for recruitment cases I and II). However, the exploitable biomass overshoots the target level and only tracks back towards the target after 2025 for both recruitment cases (Figs 5a,b). A key reason for this behaviour is that the assessment is biased (Figs 5c,d), with the average bias in exploitable biomass being ~ −10% in 2025. A reason for the bias is that the bootstrap replicate estimates of historical stock size are consistently higher than the best estimate values, which is suggestive of a conflict among the various data sources. Basing the simulations only on the 'best estimates' for the parameters of the operating model (red line in Figs 5a,b) shows a much less marked difference between the median trajectory of exploitable biomass and the target level.

Figure 6 summarizes the results for four individual simulations to better understand the behaviour of the management procedure. The assessment is always negatively biased at the start of the projection period (note that the limit reference point in the management procedure pertains to egg production which is less depleted than exploitable biomass because rock lobsters off Victoria mature before becoming vulnerable to the fishery). However, while the assessments are negatively biased for most years for the simulations in Figs 6a,c, the assessment is close to unbiased for the simulations in Figs 6b,d. As expected, the management procedure leads to the implementation of a rebuilding plan in the first year of the projection period (indicated by a "D" at the top of each panel in Fig 6). This rebuilding plan is implemented until the assessment indicates that the stock has recovered to the target level when catches are set to keep the stock close to the target level (indicated by a "I" in Fig. 6). Note that the year in which the stock assessment indicates that the stock has recovered to the target level can differ by several years from the actual recovery year due to the bias in the estimates of exploitable biomass (e.g. Fig. 6a). In two of the four cases (Fig. 6b, c), it takes more than 8 years for (perceived) recovery to occur (indicated by a "G" in Fig. 6). For some simulations (Figs 6a,b,c) the assessment indicates a decline below the target level after the initial rebuilding plan is considered complete ("D"s after 2020). In all cases these are false detections due to the bias of the assessment.

In terms of catch, the management procedure reduces catches markedly when it is first applied (Fig 7, "base") and catches recover slowly once the stock is perceived to be increasing towards the target level. As expected, the long-term catch is higher for recruitment case II than for recruitment case I (Table 1).

Single factor analyses

The results of the single-factor trials behave as expected; increasing catchability, increasing natural mortality, declining recruitment, and slower growth lead to higher levels of risk (Fig. 7a,e; Table 1) while decreasing catchability, decreasing natural mortality, increasing recruitment, and faster growth lead to lower levels of risk (Fig. 7c,g; see Supplementary Material for a list of all of the performance measures). Nevertheless, the management procedure is reasonably successful in adjusting removals to move the exploitable biomass towards the target level, and behaves as expected. The impact of the various factors on the absolute values for the performance measures differ in that a 50% increase in natural mortality is not comparable in terms of its impacts on estimation ability and the dynamics of the population to a 50% decrease in recruitment. However, some general patterns emerge from Fig. 7 and Table 1.

Time-varying catchability has the largest impact on the values for the performance measures, with the probability of the stock being above 20% of the 1951 exploitable biomass in 2050 being less than 10% irrespective of the average future recruitment when catchability is increasing. Increasing catchability also leads to the highest (even if unsustainable) catches. In contrast, decreasing catchability leads to higher stock sizes (Table 1; Figs 7c,g), but at the cost of essentially closing the fishery (Table 1; Figs 7d,h). Increasing catchability is the only single-factor scenario in which the management procedure is unable to maintain the stock above 20% of the 1951 exploitable biomass in 2050 with > 95% probability (Table 1). The poor performance of the management procedure when catchability is changing over time occurs because the primary index of abundance (catch-rate) is providing a misleading impression of stock status. Even though the other data sources (e.g. catch-in-numbers, length-frequency) are unbiased, they are unable in assessments to fully balance the effect of a biased index of abundance (Fig. 8). Nevertheless, the extent of bias in the estimates in exploitable biomass in Fig. 8 is less than the extent to which catchability is changing over time and there is a retrospective pattern in the relative errors, indicating that the catch-in-numbers and length-frequency data do tend to reduce the effect of unaccounted for time-trends in catchability to some extent. The retrospective pattern is more severe when catchability is declining over time (Fig. 8, right panels).

Ignoring the scenarios in which catchability is changing over time, exploitable biomass is above 40% of the 1951 level in 2050 with very high probability except when either future recruitment is declining or *M* is increasing (for recruitment case I). However, the need to keep the stock above the target level leads to decreasing trends in catches for these two scenarios (Figs 7b,f). The highest sustainable catches occur when either recruitment is increasing or natural mortality declining over time. Of the factors considered in the analyses, time-varying growth has the smallest impact on risk and catch.

As expected, increasing *M* and decreasing recruitment lead to more positively-biased estimates of exploitable biomass compared to the base-case and slower growth (Fig. 9a,c) while the opposite effect is evident for decreasing *M* and increasing recruitment (Fig. 9b,d). Note that trends in *M* and recruitment after 2010 impact not only bias after 2010, but also estimates of exploitable biomass for the years before 2010 for assessments conducted after 2010. The impact of trends in growth on bias in estimates of exploitable biomass is more complicated than the impact of trends in *M* or recruitment, with slower growth leading to estimates being more positively biased before 2010 and more negatively biased after 2010 (Fig. 9a,c) and faster growth having the opposite impacts (Figs 9b,d).

The median over simulations of the catch variability statistic ranges between 5 and 53%, with the cases in which catchability declines leading to the highest levels of variation in catches (Table 1).

Multifactor analyses

The multifactor analyses only consider the impact of trends in growth, natural mortality and recruitment because trends in catchability were shown to be dominant in the single factor analyses. As expected, the impacts of each factor occurring together (Fig. 10) are compounded compared to those for the single factor analyses (Fig. 7). The catches reach the maximum catch of 500t by 2040 (recruitment case I) and 2035 (recruitment case II) when all the factors act in a positive manner (faster growth, decreasing *M* and increasing recruitment). In contrast, there is only a probability of 0.21 that the exploitable biomass is above the 20% of the 1951 exploitable biomass when all factors act in a negative manner (slower growth, increasing *M* and decreasing recruitment). Even given substantially reduced catches (Figs 10b,d), the management procedure is unable to allow recovery for this worst case scenario. It is clear from Fig. 10 that the assessment is unable to adequately estimate exploitable biomass when multiple processes are non-stationary. Therefore, even though the management procedure changes catch levels in the correct direction, the amount of error is such that the stock does not stabilize at the target level.

Value of additional growth data

Updating the growth matrices every 5 years increases the probability of being above the target level for the slower growth scenario (Table 1), although this is at the cost of lower catches. Conversely, having additional information on growth leads to slightly higher catches when growth gets faster over time. The same effects are evident for the analyses in which multiple processes exhibit time-trends (Fig. 10).

Additional sensitivity tests

Three additional sets of analyses were conducted to explore the behaviour of the management procedure: (a) not upweighting the recent data and giving equal weight to all data points (separately for each data source), (b) ignoring the catch-in-numbers data, and (c) artificially increasing fishing mortality from 2006−2010 so that the stock is more depleted in 2010 (to below 20% of the 1951 exploitable biomass) than is indicated by the base case analyses. This last sensitivity test was conducted because the true (operating model) stock is initially well above the limit reference point for the other analyses. For this analysis, the data for 2006−2010 are not set to the actual data for these years, but are instead generated by the operating model. Sensitivity to ignoring the catch-in-numbers data is examined because these data are not available for most invertebrates (rock lobsters being a noteworthy exception). Results are only shown for these three additional analyses for recruitment case I because this case leads to the greatest difficulties achieving conservation objectives (Table 1).

Not upweighting the recent data leads to lower probabilities of being above the target biomass by 2050 for the base-case (Table 2, “Equal weights”) and above 20% of the 1951 exploitable biomass for the ‘all pessimistic’ case. This latter result is perhaps not expected because the data for the last years of the assessment period will tend to be very pessimistic when the assumptions of the assessment are violated because of non-stationarity of parameters. Upweighting data tends to force the assessment to place more weight on mimicking recent trends (albeit at the expense of poorer fits to the remaining data). The management procedure is able to recover the resource from a low initial state (Table 2, ”Low initial state”) although recovery to 40% of the 1951 exploitable biomass cannot be achieved by 2050 for the “all pessimistic” scenario in contrast to a scenario with higher initial biomass. Average catches are, of course, lower for this scenario. Not having catch-in-numbers data tends to lead to lower average catches and an underutilized resource (stock size well above target levels) (Table 2, “No catch-in-numbers”), which confirms the value of these data for assessment purposes.

Discussion

Non-stationarity in population and fishery parameters has been postulated for invertebrate populations (including rock lobster) (Smith and Addison, 2003; Wilberg *et al*., 2010). However, the bulk of the assessments for invertebrate stocks assume that growth and natural mortality are time-invariant (see Zheng and Siddeek (2010) for an exception to this where natural mortality is allowed to change over time), while many assessments of invertebrate stocks assume that recruitment is distributed about an average value. Commonly, stock assessments assume that catchability is constant over time. However, the assessments of rock lobster for the two Zones off South Australian estimate separate catchability parameters for before and after the introduction of quota management (McGarvey *et al*., 2010; Linnane *et al*., 2011a,b), with the assessment for the Southern Zone fishery clearly showing higher catchability subsequent to quota introduction.

The impact of time-trends in fishery processes are as would be anticipated; faster growth, decreasing natural mortality, and increasing trends in recruitment lead to higher yields and less risk while slower growth, increasing natural mortality, and decreasing trends in recruitment have the opposite effects. The lower stock sizes when growth is slower, natural mortality higher, and recruitment is decreasing are as expected, and it would have been anticipated that the management procedure would have markedly reduced catches. That the management procedure does not reduce catches sufficiently reflects the fact that the assessment is particularly biased when assumptions regarding stationarity are violated. It might have been anticipated that the assessment could have “corrected” for these effects because it estimates each annual recruitment as an estimated parameter, and because (for these simulations at least, and except when catchability is changing over time) the data are largely representative of the population. The analyses in which catchability rises indicate that the assessment results are updated in the correct direction with additional data, but that the biases remain even after many years.

Adding greater weight to recent data tends to force the assessment model to follow recent trends (at the expense of not fitting the entire data set as well). This is equivalent to making the management procedure “more empirical”, which would be expected to lead to it reacting more quickly to signals from the data.

The parameters on which most of the forecasts are based lead (on average) to more optimistic appraisals of the performance of the management strategy in terms of the rate of population rebuilding. Decision makers should be aware of this potential source of bias. However, the qualitative impacts of the various factors considered in this paper will be robust to this bias. Future research should consider basing the projections used to evaluate management strategies on a set of parameter vectors which are unbiased relative to the best estimates.

(Undetected) time-trends in catchability had the greatest impact on the performance of the management procedure. This result is not unexpected given previous evaluations of the performance of management procedures and estimation performance (e.g. Wilberg and Bence, 2006). The population is depleted severely when catchability is increasing. Although a catchability increase of ~2% per annum over 40 years seems large, this and greater extents of catchability increase have been reported in the literature (e.g. Dichmont *et al*., 2003) and estimated for the rock lobster resource in South Australia’s Northern Zone (Linnane *et al.*, 2011b). Collection of additional growth data is shown to lead to improved outcomes (biological and utilization), and analyses to detect changes in growth have been explored in the past for rock lobster off Victoria (Punt *et al.*, 2006b) and at present (T.I. Walker, pers. comm).

In principle, were it possible to relate potential changes in biological parameters to specific environmental variables, it might be possible to develop a management procedure which performs better. However, identifying such relationships has proven difficult in general, and the value of knowing the relationship between environmental variables may be limited unless the relationship is particularly strong (Basson, 1999; De Oliveira and Butterworth, 2005).

The possibility of a lack of stationarity in biological parameters, in particular, the stock-recruitment relationship has been long-recognized (e.g. Walters, 1987), and potential harvest control rules have been evaluated in the context of non-stationarity (Parma and Deriso, 1990; Butterworth and Punt, 1999; A’mar *et al*., 2009), but most evaluations of management procedures assume that relationships governing biological process do not change over time. Moreover, most studies that have considered non-stationarity have only focused on recruitment processes, even though natural mortality, growth and catchability could all exhibit trends over time (although evaluations of management procedures for rock lobsters off South Africa have accounted for possible changes in natural mortality and growth; Johnston and Butterworth, 2005).

The results of the present paper confirm the importance of accounting for non-stationarity when evaluating management procedures. Feedback control management procedures should be able to "learn" over time, and the results suggest that this is indeed the case. However, these results also suggest that long-term changes in catchability are unlikely to be corrected for, even when there are several sources of data that are unimpacted by changes in catchability. The impacts of time-trends in growth and natural mortality were relatively inconsequential. Regular collection of data on growth (as already occurs off Victoria through long-term tagging studies; Punt *et al.*, 2006b) will tend to correct for the impacts of changes over time in growth. Unfortunately, unlike growth, natural mortality is a notoriously difficult parameter to estimate, and estimating time-trends in natural mortality except through the use of ecosystem models is infeasible at present and in the short- to medium-term. Finally, the assessment provides a way to estimate trends in recruitment. In context of the management procedure for Victorian rock lobster, trends in recruitment are particularly problematic as they imply long-term changes in the target biomass level. Although changing the window over which recruitments are generated will tend to account for changes in expected future likely recruitment, it cannot address the impact on target biomass levels. Changing target levels to mimic the current regime should, in principle, address the issue but this approach is problematic owing to problems such as identifying when a regime has changed and estimating average recruitment in a new regime (e.g. A'mar *et al.*, 2009; Szuwalski and Punt, in press).

The management procedure evaluated in this paper is "model-based" and hence integrates data over many years. It is possible that the impacts of time-trends in biological parameters on empirical approaches to setting harvest limits (such as the management procedures used for rock lobsters off South Africa and South Australia's southern zone) would differ (and potentially be more severe) as they tend to place greatly weight on recent data, and warrant further investigation.

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Table 1. Values for key performance measures for the base-case analyses, the single-factor trials, and the trials in which changes occur simultaneously in natural mortality, recruitment, and growth. Results are shown for the recruitment cases and when future data are and are not available on growth (the results when data on growth are available are shown in parentheses). The probability measures relate to the probability of being above limit and target reference points in terms of exploitable biomass.

Scenario	Recruitment case I				Recruitment case II			
	P(Above Limit in 2050)	P(Above Target in 2050)	Median Catch (40 yrs)	Median AAV	P(Above Limit in 2050)	P(Above Target in 2050)	Median Catch (40 yrs)	Median AAV
Base	100	94	111.9	0.15	100	98	159.5	0.14
Increasing Q	4	0	219.0	0.12	2	0	256.1	0.08
Increasing M	100	8	64.6	0.20	100	58	100.0	0.17
Slower growth	100	43	93.4	0.16	100	72	133.8	0.15
	(100)	(73)	(81.0)	(0.17)	(100)	(86)	(126.6)	(0.15)
Decreasing R	100	26	66.3	0.20	100	73	99.3	0.17
All Pessimistic	79	0	35.7	0.26	100	0	53.3	0.22
	(95)	(0)	(29.6)	(0.28)	(100)	(0)	(46.5)	(0.23)
Decreasing Q	100	100	10.5	0.53	100	100	19.4	0.35
Decreasing M	100	100	183.6	0.12	100	100	235.0	0.10
Faster growth	100	98	121.0	0.14	100	100	173.7	0.13
	(100)	(98)	(130.8)	(0.14)	(100)	(99)	(179.8)	(0.13)
Increasing R	100	99	162.8	0.13	100	100	218.7	0.11
All Optimistic	100	100	243.4	0.07	100	100	261.7	0.05
	(100)	(100)	(250.3)	(0.07)	(100)	(100)	(261.7)	(0.05)

Table 2. Values for key performance measures for the base-case analysis and the “all pessimistic” analysis, as well as for analyses which change the weights assigned to recent data and which start the projections from a lower initial state. The results are based on recruitment case I. The probability measures relate to the probability of being above limit and target reference points in terms of exploitable biomass.

Scenario	Base case				All Pessimistic			
	P(Above Limit in 2050)	P(Above Target in 2050)	Median Catch (40 yrs)	Median AAV	P(Above Limit in 2050)	P(Above Target in 2050)	Median Catch (40 yrs)	Median AAV
From Table 1	100	94	111.9	0.15	79	0	35.7	0.26
Equal weights	100	70	122.7	0.13	21	0	54.7	0.20
Low initial state	100	85	28.0	0.26	29	0	25.6	0.30
No catch-in-numbers	100	99	92.6	0.16	94	0	24.5	0.30

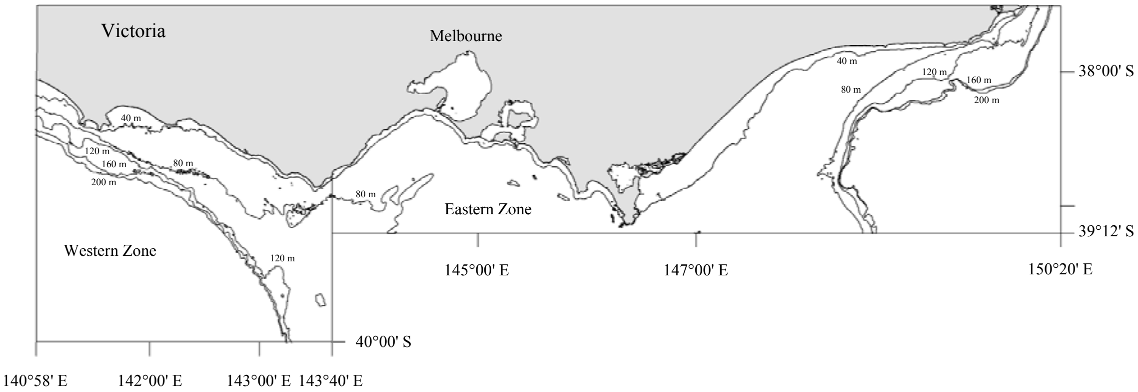


Figure 1. Western Zone extends south of Victoria to latitude 40°00'S and is bounded by longitude 140°58'E in west and 143°40'E in the east and Eastern Zone extends south of Victoria to latitude 39°12'S and is bounded by longitude 143°40'E in the west and 150°20'E in the east (shown with 40-m depth contours).

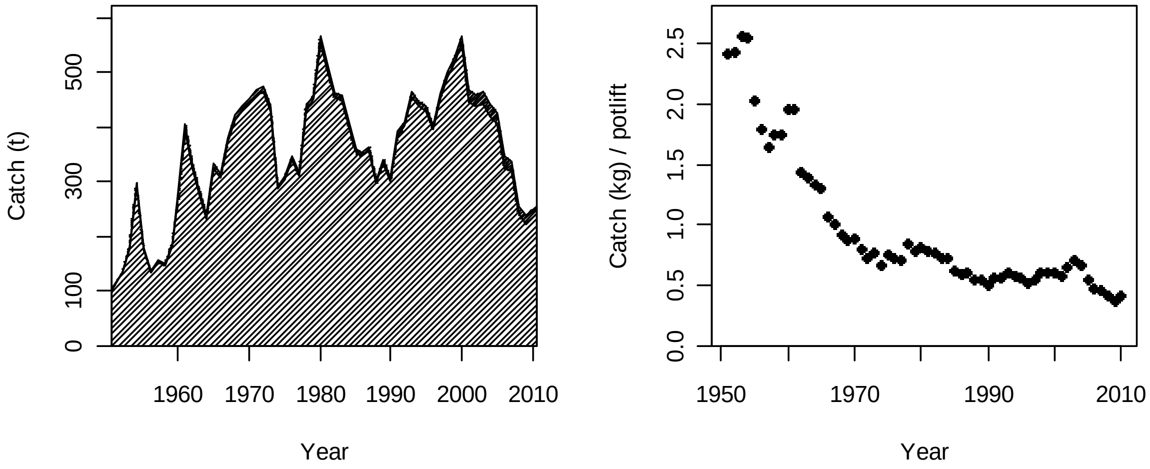


Figure 2. Catch (hashed – commercial; solid – recreational) and commercial catch-rate trajectories for Victoria's Western Zone rock lobster fishery.

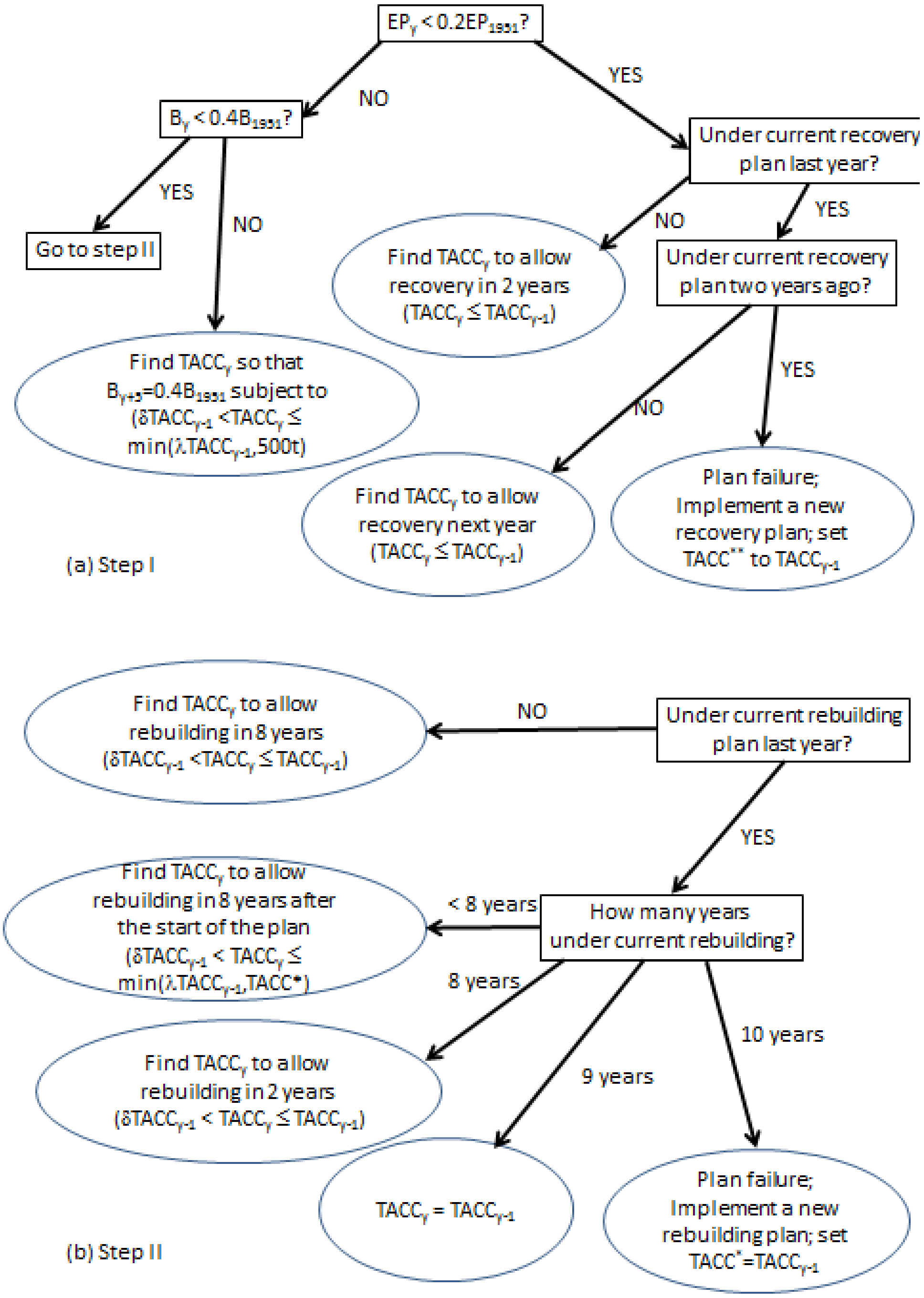


Figure 3. Outline of the harvest control rule. "EP" denotes egg production and "B" exploitable biomass. TACC** is the maximum TACC during a recovery plan and TACC* is the maximum TACC during a rebuilding plan. The values of TACC* and TACC** are ignored once recovery or rebuilding, occurs.

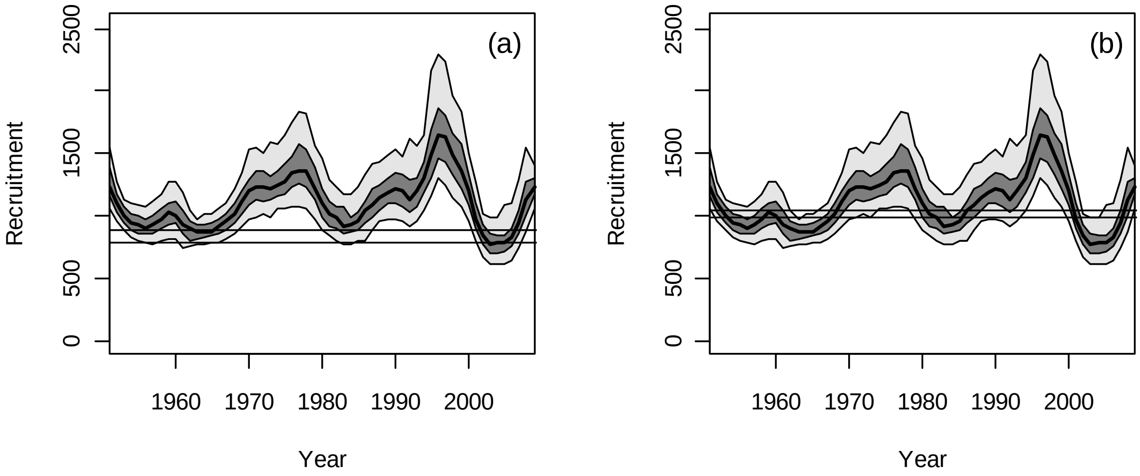
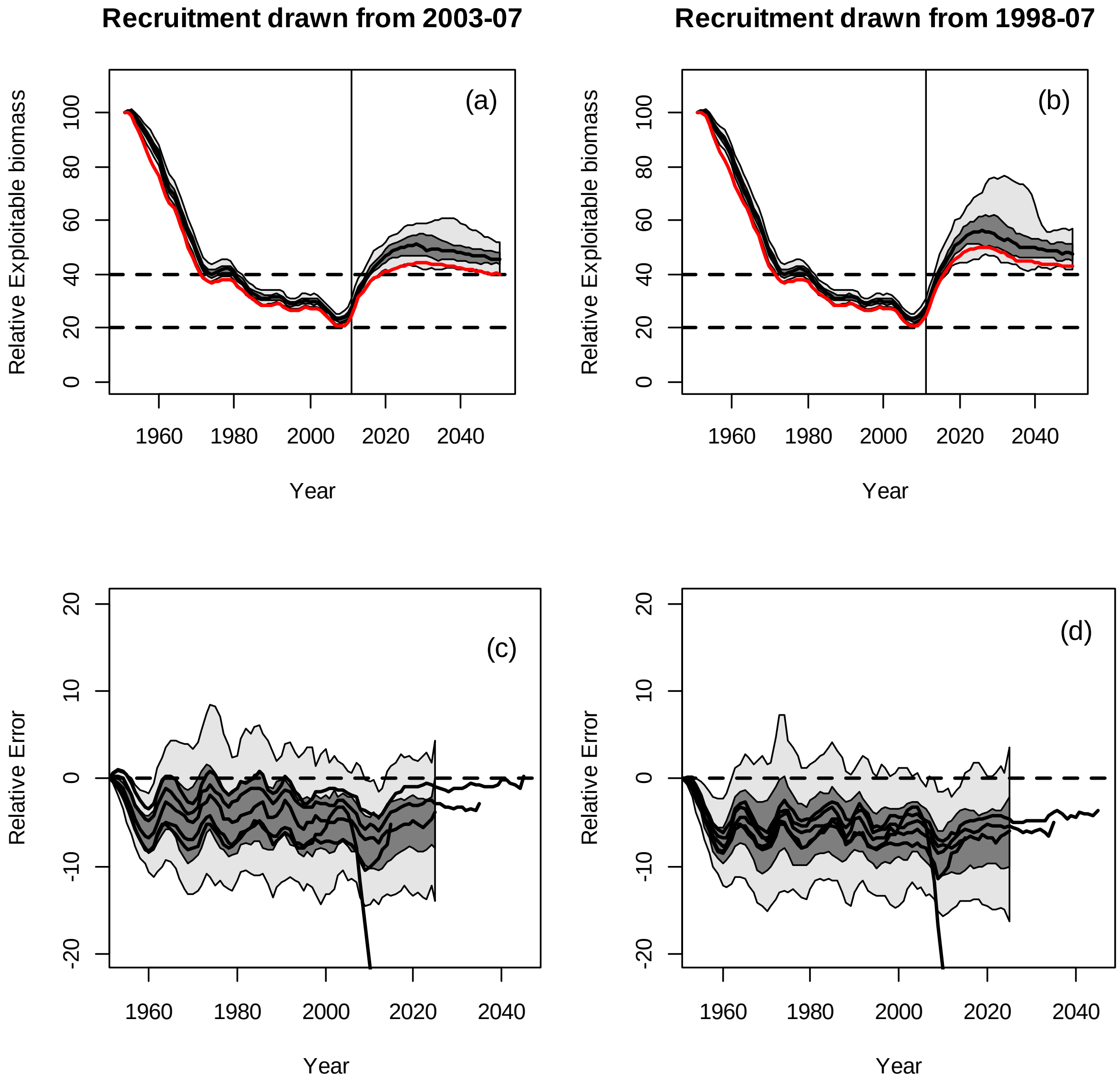


Figure 4. Time-trajectories of recruitment (dark solid line median; dark shading 50% simulation intervals; light shading 90% simulation intervals). The horizontal bars indicate the distribution (25-75%iles) of mean recruitment from 2003-07 (a) and 1998-2007 (b).



Recruitment drawn from 2003-07

Recruitment drawn from 1998-07

Figure 5. Upper Panels: Time-trajectories of exploitable biomass (solid line median; dark shading 50% simulation intervals; light shading 90% simulation intervals) for the reference case analyses; the solid red line indicates the median time-trajectory of exploitable biomass from the reference case simulations in which the parameters of the operating model are set to the 'best' estimates rather than being drawn from a bootstrap distribution. Lower Panels: Time-trajectories of relative error for exploitable biomass relative to the level in 1951 (solid lines medians in various assessment years; dark and light shading 50% and 90% simulation intervals for assessments conducted in 2025).

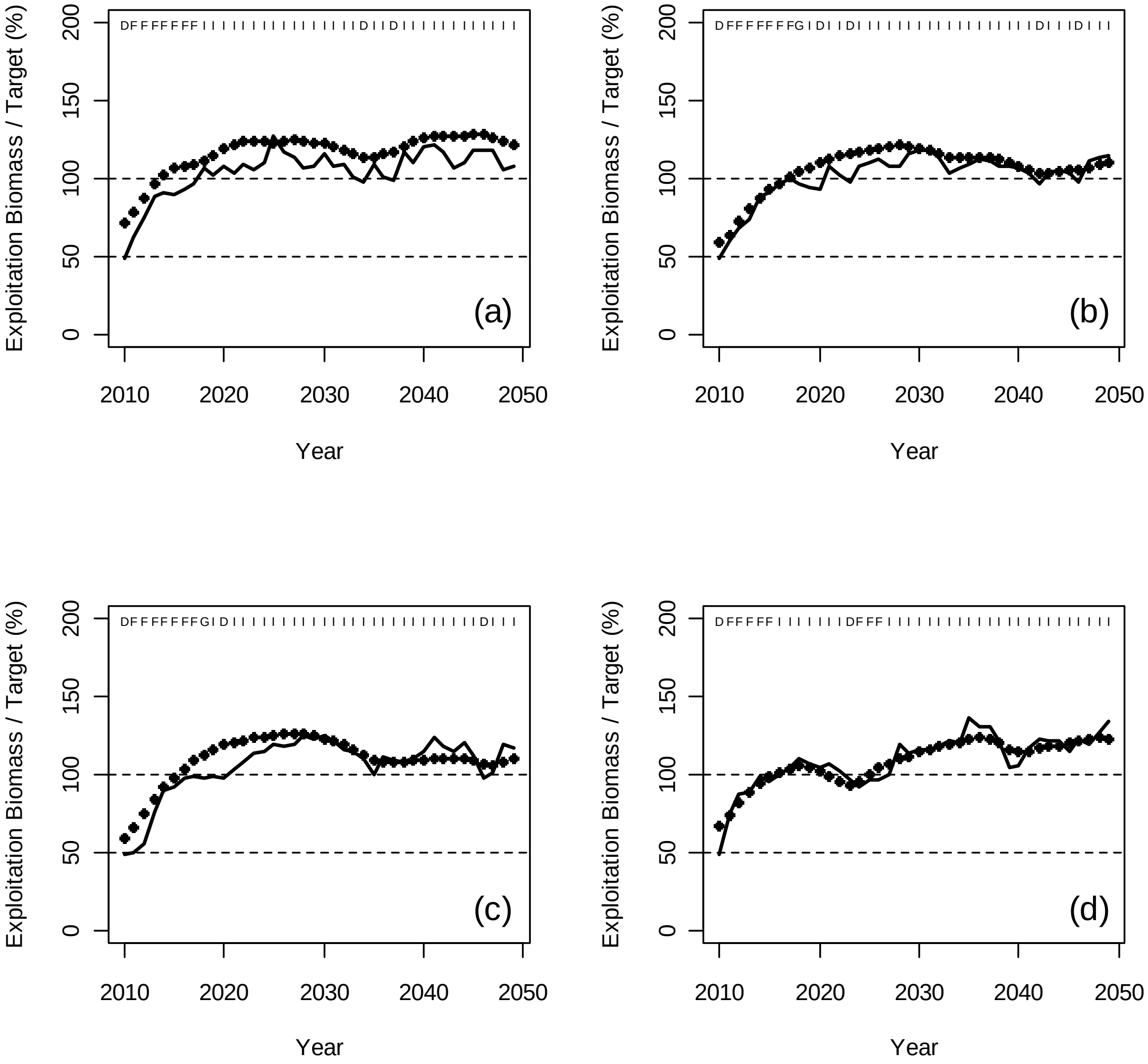


Figure 6. Time-trajectories of true (operating model) exploitable biomass (dots) and the annual estimates from the stock assessment (lines) (i.e. the value for 2020 is the outcome of the assessment conducted in 2020) for four individual simulations chosen at random. The symbols at the top of the panels indicate which step of the management procedure was used to calculate the TACC: "D" newly declared to be need of a rebuilding plan, "F" under a rebuilding plan", "G" in the 9th year of the rebuilding plan, and "I" recovered to above the target level.

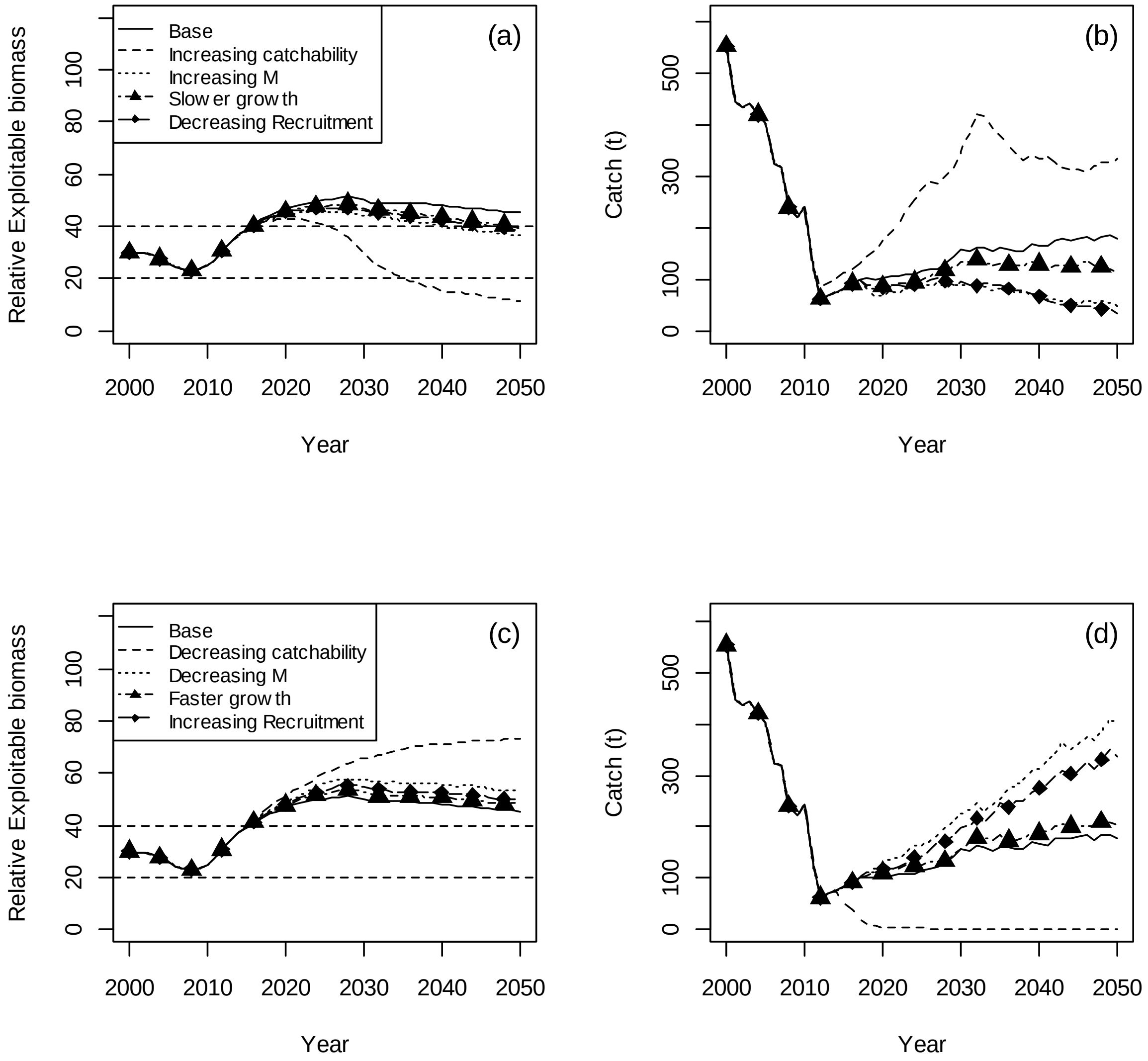
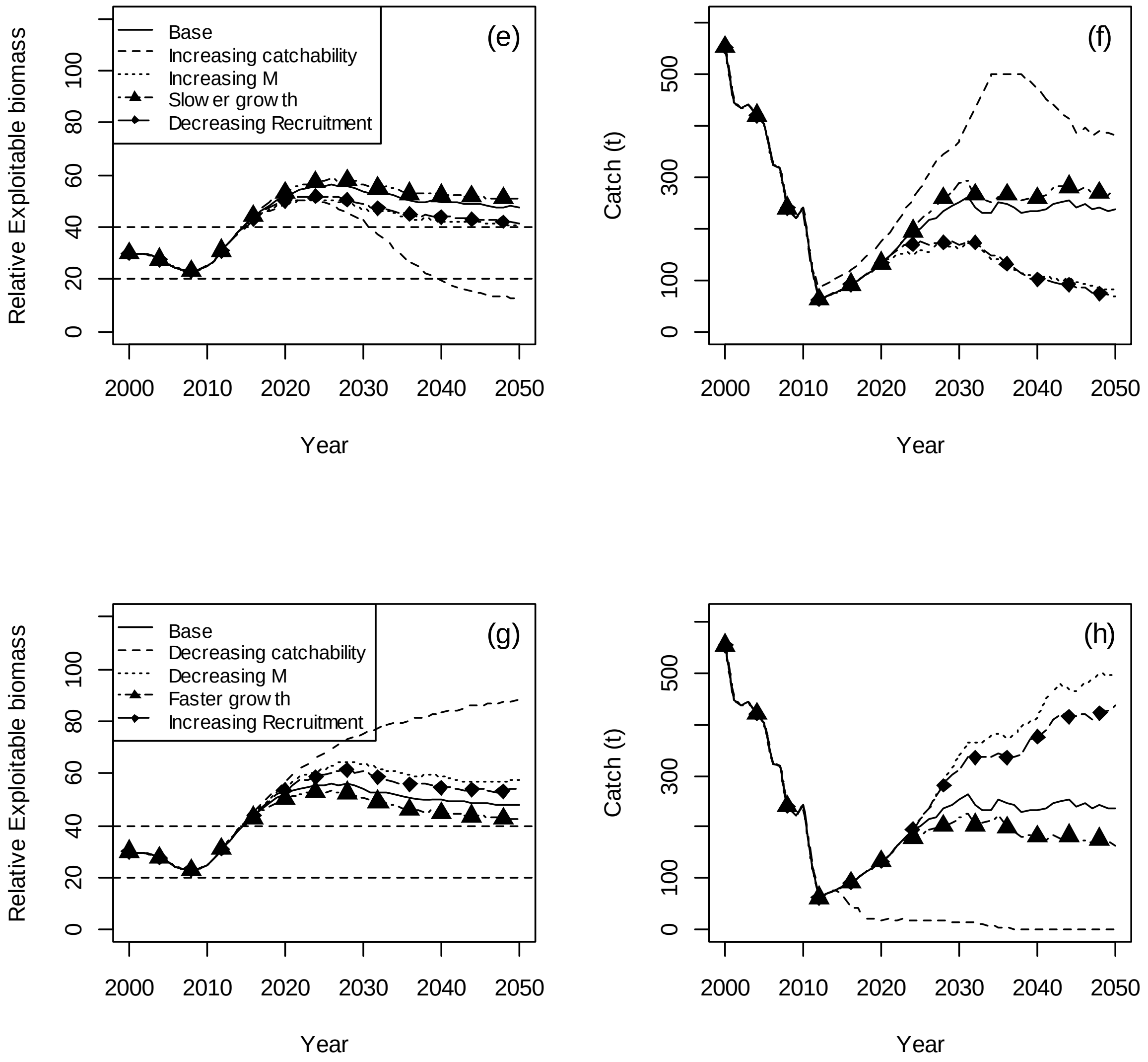


Figure 7. Time-trajectories (medians of 100 simulations) of exploitable biomass relative to the 1951 level (left panels) and catch (right panels) for the base-case analyses and for the simulations in which a single biological or fishery parameter exhibits a time-trend. Results are shown for recruitment case I in a–d, and for recruitment case II in e–h.



(Figure 7 Continued)

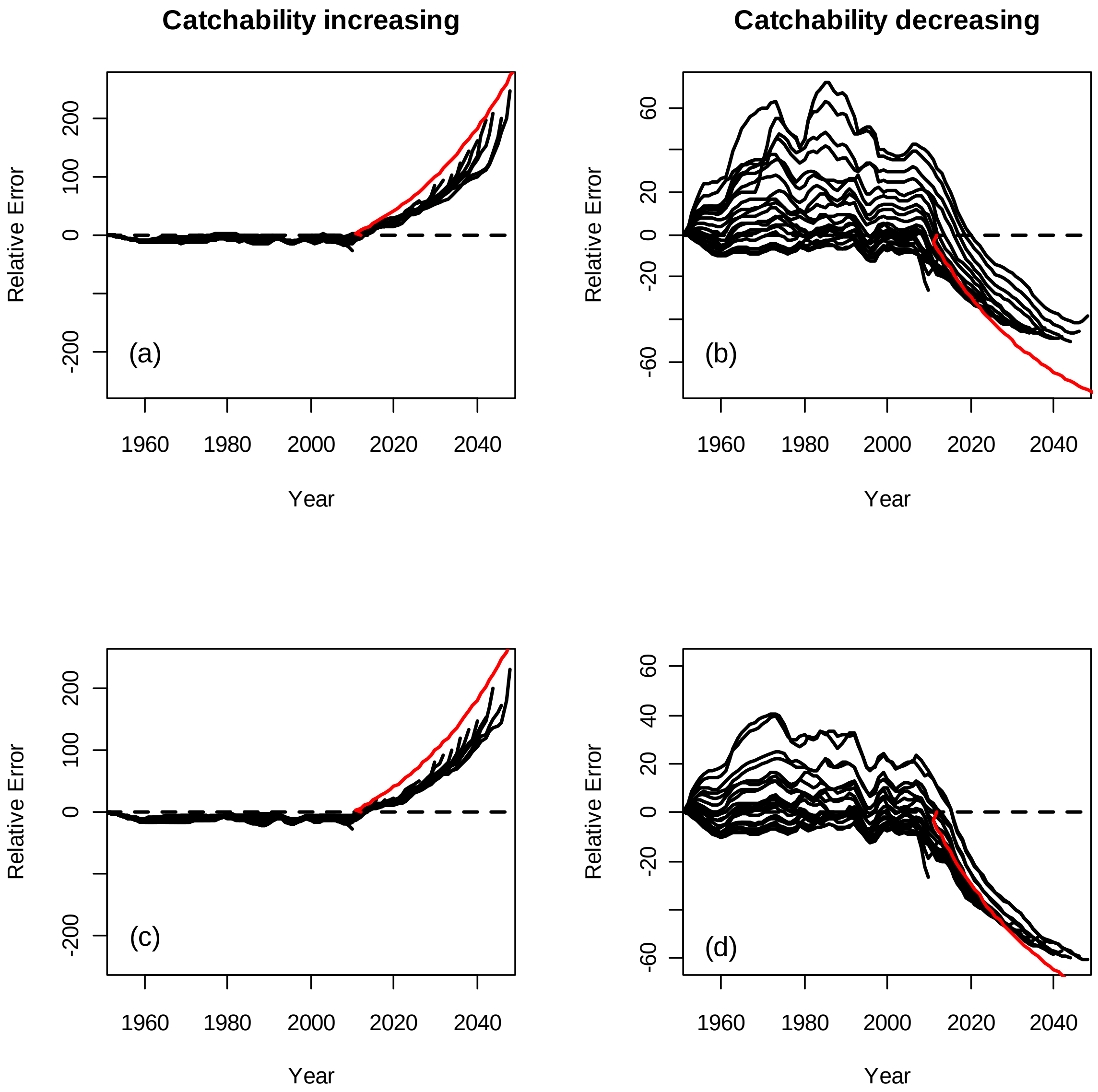


Figure 8. Time-trajectories of median relative error (in the estimates in exploitable biomass) for assessments conducted in 2010, 2012, etc. for the scenarios in which catchability exhibits a trend with time. Results are shown in the upper panels for recruitment case I and in the lower panels for recruitment case II. The red line indicates the change in catchability relative to 2010.

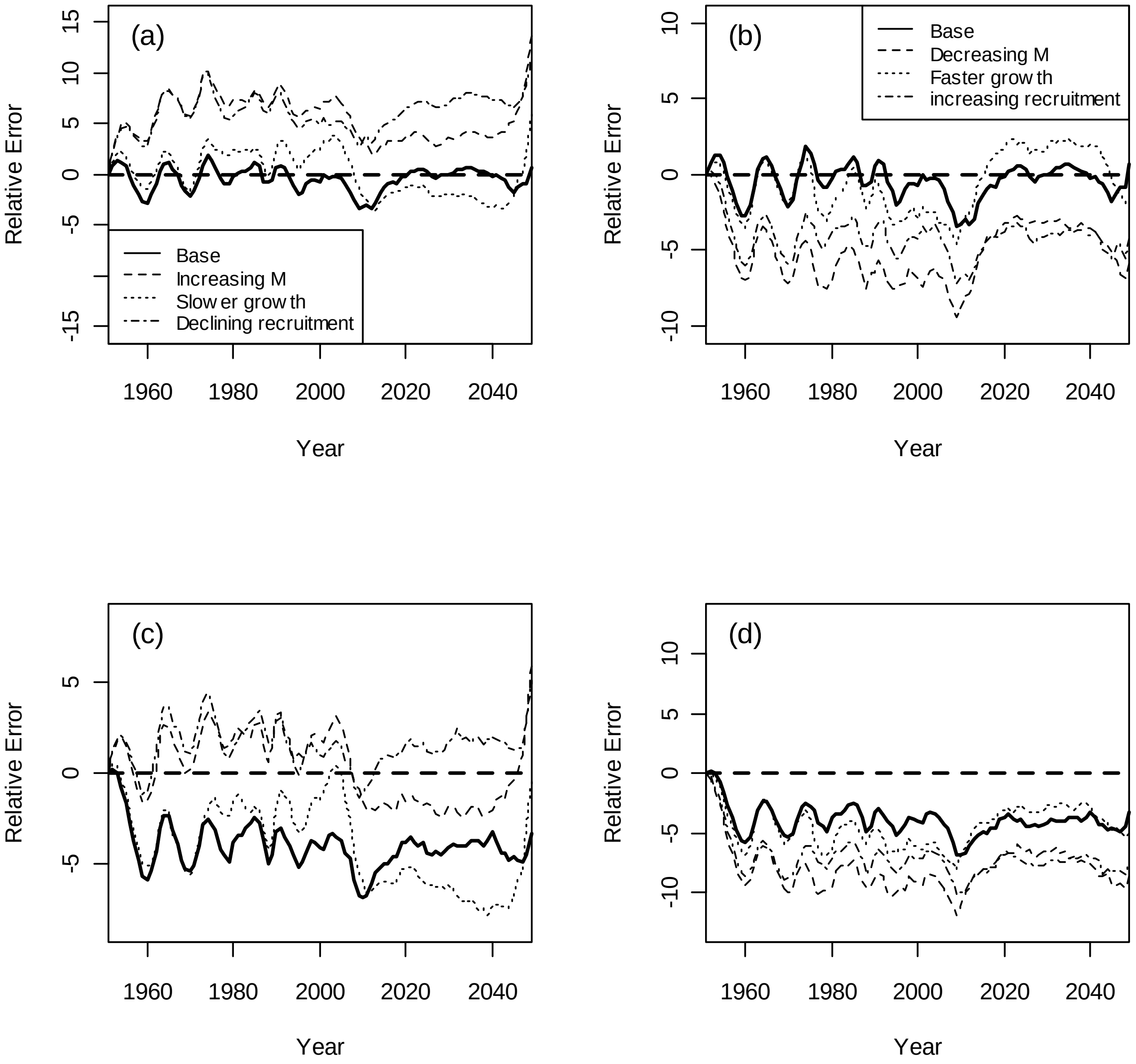


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Figure 9. Time-trajectories of median relative error for assessments conducted in 2049. Results are shown in the upper panels for recruitment case I and in the lower panels for recruitment case II.

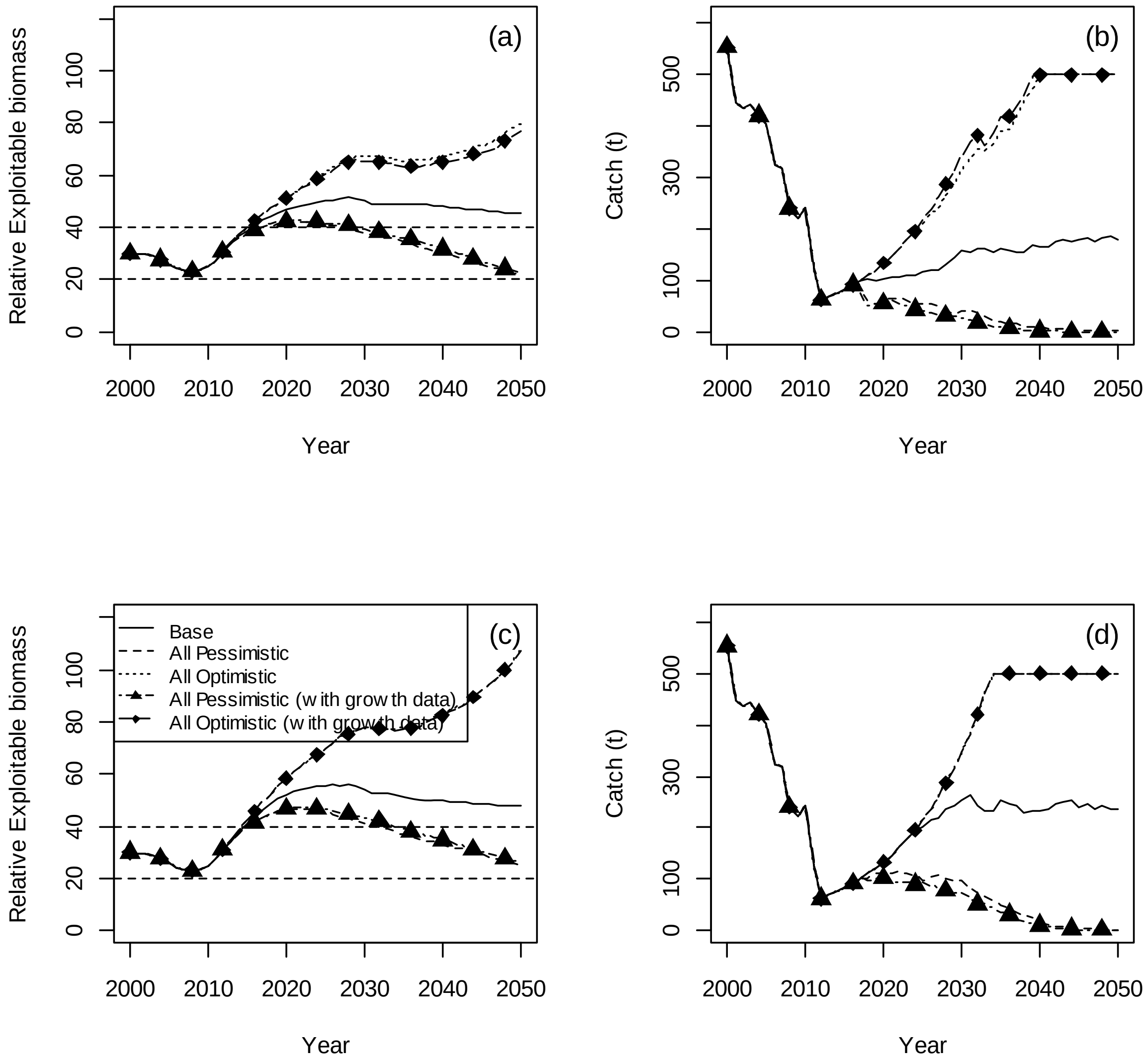

Figure 10. Time-trajectories (medians of 100 simulations) of exploitable biomass relative to the 1951 level (left panels) and catch (right panels) for the base-case analyses and the simulations in which natural mortality, growth, and recruitment simultaneously exhibit time-trends. Results are shown for recruitment case I in a–b, and for recruitment case II in c–d.

Specifications for a Generalized Spatial Rock Lobster Model

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The population dynamics model is spatially-structured, and operates on a user-specified set of time-steps (which need not all be of the same duration). The spatial strata in the model are referred to as "sub-zones" (indexed by "z") and the number of time-steps each year is *T*. The duration of the i^{th} time-step (i=0,1,..,T-1) is denoted t_i and, by definition, $\sum_{i=0}^{T-1} t_i = 1$. The time-steps are such that the model can be run with any definition of "year" (e.g. "calendar year" or "quota year"). Growth, fishing, and movement, establishment of a MPA, and settlement (number of animals entering the model; not the same as recruitment to the exploitable biomass) can occur during any of the time-steps.

A. The population dynamics model

A.1 Basic dynamics

The equation that specifies the number of animals of sex *s* in size-class *l* in sub-zone *z* at the start of time-step *i* of year *t* takes account of natural mortality, fishing mortality, movement, growth, and settlement. Assuming that harvest occurs before growth and settlement, after which movement occurs:

$$N^{s,z}_{y,i+1,l} = \sum_{z'} Y_i^{s,z,z'} \left[\sum_{l'} X^{s,z'}_{l',l,y,i}\, N^{s,z'}_{y,i,l'}\, e^{-Mt_i} \{1-\tilde{H}^{s,z'}_{y,i,l'}\} + \Omega_i^{s,z'} \Phi_l^s\, R_y^{z'} \right] \tag{A.1}$$

where $N^{s,z}_{y,i,l}$ is the number of animals of sex *s* in size-class *l* in sub-zone *z* at the start of time-step *i* of year *y* (the size-classes range from 1 to n_L^s), $X^{s,z}_{l',l,y,i}$ is the faction of the animals of sex *s* in size-class *l'* in sub-zone *z* that grow into size-class *l* during time-step *i* of year *y* (the possibility of shrinkage is ignored), $Y_i^{s,z,z'}$ is the fraction of the animals of sex *s* that move from sub-zone *z'* to sub-zone *z* at the end of time-step *i*, *M* is instantaneous rate of natural mortality (assumed to be independent of sex, size, sub-zone, and time), $\tilde{H}^{s,z}_{y,i,l}$ is the exploitation rate on animals of sex *s* in size-class *l* and sub-zone *z* at the start of time-step *i* of year *y*:

$$\tilde{H}^{s,z}_{y,i,l} = \sum_{f \in f_z} \tilde{S}^{s,f}_{y,i,l} (1-\tilde{p}^{s,z}_{i,l})(1-H^{s,f}_{y,i,l}) V_i^s\, F^f_{y,i} \tag{A.2}$$

V_i^s is the relative vulnerability of males to females during time-step *i* (V_i^s=1 for males), $\tilde{p}^{s,z}_{i,l}$ is the proportion of animals of sex *s* in sub-area *z* in length-class *l* which are returned live during time-step *i* because they are spawning, $H^{s,f}_{y,i,l}$ is the proportion of animals of sex *s* in length-class *l* which are returned live during time-step *i* of year *y* by fleet *f* because of high-grading, $\tilde{S}^{s,f}_{y,l}$ is the vulnerability of the gear used by fleet *f* on animals of sex *s* in size-class *l* during time-step *i* of year *y* given the implications of the legal minimum size:

$$\tilde{S}^{s,f}_{y,i,l} = \begin{cases} 0 & \text{if } L_l^s + \Delta L_l^s \le \text{LML}_y^{s,f} \\ S^{s,f}_{y,i,l} & \text{if } L_l^s \ge \text{LML}_y^{s,f} \\ S^{s,f}_{y,i,l}(L_l^s + \Delta L_l^s - \text{LML}_y^{s,f}) / \Delta L_l^s & \text{otherwise} \end{cases} \tag{A.3}$$

f_z is the set of fleets which are found in sub-zone *z*, L_l^s is the lower limit of size-class *l* for sex *s*, ΔL_l^s is the width of a size-class *l* for sex *s*, $\text{LML}_y^{s,f}$ is the legal minimum size for sex *s* and fleet *f* during year *y*, $S^f_{y,i,l}$ is the vulnerability of the gear used by fleet *f* on animals of sex *s* in size-class *l* during time-step *i* of year *y*, $F^f_{y,i}$ is the exploitation rate on fully-selected (i.e. $\tilde{S}^{s,f}_{y,l} = 1$) animals by fleet *f* during time-step *i* of year *y*, $\Omega_i^{s,z}$ is the fraction of the settlement to sub-zone *z* that occurs to sex *s* during time-step *i* ($\sum_s \sum_i \Omega_i^{s,z} = 1$), Φ_l^s is the proportion of the settlement of animals of sex *s* that occurs to size-class *l* ($\sum_l \Phi_l^s = 1$), and R_y^z is the settlement of animals to sub-zone *z* during year *y*.

Allowance is made for vulnerability to differ among years to implement possible past and future changes in vulnerability due to changes to legal minimum sizes, gear configurations and where fishing occurs within sub-zones. Vulnerability can also account for discarding (live), as well as high-grading by fishers.

Allowance is also made for settlement to occur to any size-class, during any time-step and in different ratios for males and females. However, by pre-specifying the values for the $\Omega_i^{s,z}$ and Φ_l^s, it is possible implement simpler models such as that the sex-ratio of settlement is 50:50, occurs to one size-class only, and only happens during one time-step. For ease of parameter estimation, the annual settlements are parameterized as follows:

$$R_y^z = \overline{R}_y^z \, e^{\varepsilon_y^z - (\sigma_{R,y})^2/2} \qquad \text{(A.4)}$$

where $\overline{R}_y^z$ is mean settlement to sub-zone *z* during year *y*, ε_y^z is the "settlement residual" for year *y* and sub-zone *z*, $\sigma_{R,y}$ is the standard deviation of the random fluctuations in settlement for year *y*:

$$\sigma_{R,y}^2 = \begin{cases} \tilde{\sigma}_R^2 \, \tilde{\tau}^{(y-y_{\text{start}})} & \text{if } y < y_{start} \\ \tilde{\sigma}_R^2 & \text{otherwise} \end{cases} \qquad \text{(A.5)}$$

$\tilde{\sigma}_R$ is the extent of variation in settlement for years after y_{start}, and $\tilde{\tau}$ determines the extent to which σ_R changes with time.

Mean settlement is either an estimated constant or related to egg production by means of the Beverton-Holt stock-recruitment relationship, i.e.:

$$\overline{R}_y^z = \frac{4hR_0^z \tilde{B}_{y-\tilde{L}}^z / \tilde{B}_0^z}{(1-h) + (5h-1)\tilde{B}_{y-\tilde{L}}^z / \tilde{B}_0^z} \qquad \text{(A.6)}$$

where *h* is the steepness of the stock-recruitment relationship, $\tilde{B}_y^z$ is the egg production in sub-zone *z* during year *y*, $\tilde{L}$ is the lag between spawning and settlement. Egg production is given by the following equation for the case in which spawning is assumed to occur at the start of time-step i_m:

$$\tilde{B}_y^z = \sum_l Q_l^z \, N_{y,i_m,l}^{\text{f},z} \qquad \text{(A.7)}$$

where Q_l^z is the expected number of eggs produced by a female in size-class *l* in sub-zone *z*, and i_m is the time-step in which spawning occurs. The $\tilde{B}_0^z$ is computed from the value for the parameter R_0^z and the unfished egg production-per-recruit.

The annual recruitment to the fishable population during a time-step is the number of animals that reach the legal minimum size during that time-step plus any animals that settle during that time-step at sizes larger than the legal minimum size.

A.2 Catches

The fully-selected exploitation rate for fleet *f* during time-step *i* of year *y*, $F_{y,i}^f$, is calculated by using Equation A.8a if catches are specified in mass and using Equation A.8b if they are specified in numbers:

$$F_{y,i}^f = \frac{C_{y,i}^f}{\sum_l \sum_s \tilde{S}_{y,i,l}^{s,f} \, (1-\tilde{p}_{i,l}^{s,z})(1-H_{y,i,l}^{s,f})V_l^s \, W_l^{s,z_f} \, \tilde{N}_{y,i,l}^{s,z_f}} \qquad \text{(A.8a)}$$

$$F^f_{y,i} = \frac{C^f_{y,i}}{\sum_l \sum_s \tilde{S}^{s,f}_{y,i,l}(1-\tilde{p}^{s,z_f}_{i,l})(1-H^{s,f}_{y,i,l})V^s_l \; \tilde{N}^{s,z_f}_{y,i,l}} \tag{A.8b}$$

where $C^f_{y,i}$ is the catch by fleet *f* during time-step *i* of year *y* (equal to the landed catch multiplied by one plus the ratio of numbers landed to discards which die), $\tilde{N}^{s,z}_{y,i,l}$ is the number of animals of sex *s* in size-class *l* in sub-zone *z* when the catch during time-step *i* of year *y* is removed, z_f is the sub-zone in which fleet *f* operates, and $W^{s,z}_l$ is the mass of an animal of sex *s* in size-class *l* and sub-zone *z*.

Equation (A.8) implies the assumption that discard mortality is negligible compared with fishing mortality.

A.3 Initial conditions

It is impossible to project this model from unexploited equilibrium owing to a lack of historical catch records for the entire period of exploitation. Instead, it is assumed that the population was in equilibrium with respect to the average catch over the first ω years for which catches are available in year $y_{start}-\chi$. This approach to specifying the initial state of the stock differs from that traditionally adopted for assessments of rock lobster off Tasmania and Victoria (Punt and Kennedy, 1997; Hobday and Punt, 2001) in that no attempt is made to estimate an initial exploitation rate. The settlements for years $y_{start}-\chi$ to $y_{start}-1$ can be treated as estimable so that the model is not in equilibrium at the start of year y_{start}. The exploitation rate for the years $y_{start}-\chi$ to $y_{start}-1$ are set to the value used to calculate the size structure between years y_{start} and $y_{start}+\omega$ (F^z_{init}) where both ω and χ are pre-specified constants.

A.4 Allowing for Marine Protected Areas

The approach to allow for Marine Protected Areas follows Hobday *et al.* (2005). Each MPA is assigned to a "home" sub-zone and its dynamics follow Equation A.1, including movement between the MPA and the sub-zone in which it is located. The settlement for each sub-zone is allocated to the areas open and closed to fishing within the sub-zone based on the size of the MPA relative to the total area of the sub-zone (i.e. the "area" of an MPA is the proportion of the total settlement to the sub-zone in which it located which settles in the MPA).

B. The objective function

The objective function summarises the information collected from the fishery and contains contributions from five data sources:

a) commercial catch rates,
b) length-frequency data,
c) commercial catches in number,
d) an index of settlement (based, for example, on puerulus data), and
e) tagging data (separately to estimate movement rates and growth).

It is not necessary to have all these types of data to estimate the values for the parameters of the model (see Table 1).

B.1 Catch-rate data

The contribution of the catch-rate data for the commercial and recreational fleets to the likelihood function is given by:

$$L_1 = \prod_f \prod_y \prod_i \frac{1}{I^f_{y,i}\sqrt{2\pi}\,\sigma^f_{q,y,i}} \exp\left(-\frac{(\ell n I^f_{t,i} - \ell n(q^f_i \overleftrightarrow{q}^f_{y,i} B^{e,f}_{y,i}))^2}{2(\sigma^f_{q,y,i})^2} \right) \tag{B.1a}$$

while the contribution of fisheries independent index (FIMS) data to the likelihood function is given by:

$$L_1 = \prod_f \prod_y \prod_i \frac{1}{K^f_{y,i}\sqrt{2\pi}\,\tilde{\tilde{\sigma}}^f_{q,y,i}} \exp\left(-\frac{(\ell n K^f_{t,i} - \ell n(q^f_i \overleftrightarrow{q}^f_{y,i} \tilde{\tilde{q}}^{f_{z,f}} \; B^{e,f}_{y,i}))^2}{2(\tilde{\tilde{\sigma}}^f_{q,y,i})^2} \right) \tag{B.1b}$$

where $\sigma^f_{q,y,i}$ is the standard deviation of the random fluctuations in catchability for catch-rate for commercial/recreational fleet *f*, year *y*, and time-step *i*, $\tilde{\tilde{\sigma}}^z_{q,y,i}$ is the standard deviation of the random fluctuations in catchability for FIMS fleet *f* during time-step *i* of year *y*, q^f_i is the catchability coefficient for commercial/recreational fleet *f* and time-step *i*, $\tilde{\tilde{q}}^f$ is the FIMS catchability coefficient FIMS series *f*, $\overleftrightarrow{q}^f_{y,i}$ is the trend in catchability due to environmental or fishery factors, i.e. $\overleftrightarrow{q}^f_{y,i} = \exp\left(\sum_j \theta^{f,j}_i E^j_y\right)$, $f_{z,f}$ is the commercial fleet which operates in the same sub-zone as FIMS fleet *f*, $I^f_{y,i}$ is the catch-rate index for commercial/recreational fleet *f*, year *y*, and time-step *i*, E^j_y is the value for the jth environmental / fishery index for year *y*, $\theta^{f,j}_i$ is the parameter which links catchability for fleet *f* during time-step *i* and environmental variable *j*, $K^f_{y,i}$ is the FIMS index for FIMS fleet *f*, during time-step *i* of year *y*, and $B^{e,f}_{y,i}$ is the exploitable biomass available to fleet *f* during time-step *i* of year *y* (the biomass available to the fleet less half of the catch time-step *i* of year *y*) if the catch-rate index relates to catch-rate (commercial fishery or a survey):

$$B^{e,f}_{y,i} = \sum_s \sum_l V^s_l \, \tilde{S}^{s,f}_{y,i,l} \, W^{s,z}_l \, (\tilde{N}^{s,z_f}_{y,i,l} - C^{s,z_f}_{y,i,l}/2) \tag{B.2a}$$

while it is

$$B^{e,f}_{y,i} = \sum_s \sum_l V^s_l \, \tilde{S}^{s,f}_{y,i,l} \, \tilde{N}^{s,z_f}_{y,i,l} \tag{B.2b}$$

if the catch-rate is a pre-recruit index.

$C^{s,z}_{y,i,l}$ is the catch of animals of sex s in size-class l in sub-zone z during time-step *i* of year *y*:

$$C^{s,z}_{y,i,l} = \sum_{f \in z} V^s_i \tilde{S}^{s,f}_{y,i,l} (1 - \tilde{p}^{s,z}_{i,l})(1 - H^{s,f}_{y,i,l}) W^{s,z}_i \tilde{N}^{s,z}_{y,i,l} F^f_{y,i} \tag{B.3}$$

The maximum likelihood estimate for q^f_i can be obtained analytically (the values for the $\tilde{\tilde{q}}^f$ are estimated as part of the non-linear search procedure):

$$\hat{q}^f_i = \exp\left(\sum_y \ell\text{n}(I^f_{y,i} / \overleftrightarrow{q}^f_{y,i} B^{e,f}_{y,i}) / (\sigma^f_{q,y,i})^2 \Big/ \sum_y 1/(\sigma^f_{q,y,i})^2 \right) \tag{B.3a}$$

$$\hat{q}^f_i = \exp\left(\frac{\sum_y \ell\,\text{n}(I^f_{y,i} / \overleftrightarrow{q}^f_{y,i} B^{e,f}_{y,i}) / (\sigma^f_{q,y,i})^2 + \sum_y \ell\,\text{n}(K^f_{y,i} / (\tilde{\tilde{q}}^f \overleftrightarrow{q}^f_{y,i} B^{e,f}_{y,i})) / (\tilde{\tilde{\sigma}}^f_{q,y,i})^2}{\sum_y 1/(\sigma^f_{q.y,i})^2 + \sum_y 1/(\tilde{\tilde{\sigma}}^f_{q,y,i})^2} \right) \tag{B.3b}$$

Allowance is made for the possible changes in catchability between groups of years by treating each period in which catchability is constant as a separate catch-rate index. The values for the residual standard deviations can also be estimated analytically.

B.2 Length-frequency data

Length-frequency data are available for the commercial/recreational catch and from research sampling. The commercial length-frequency data provide information on the proportion of the (landed) catch of each sex in each size-class above the legal minimum size, while the research length-frequency data also provide information on the number of animals of legal minimum size and smaller. The observed fraction of the landed catch of animals of sex *s* in number during time-step *i* of year *y* by fleet *f* that are in size-class *l* is denoted $\rho^{s,f}_{y,i,l}$. The model-estimate of this quantity, $\hat{\rho}^{s,f}_{y,i,l}$, takes account of the vulnerability of the gear and the numbers in each size-class:

$$\hat{\rho}^{s,f}_{y,i,l} = \tilde{S}^{s,f}_{y,i,l}(1-\tilde{p}^{s,z_f}_{i,l})(1-H^{s,f}_{y,i,l})\tilde{N}^{s,z_f}_{y,i,l} / \sum_{l'} \tilde{S}^{s,f}_{y,i,l'}(1-\tilde{p}^{s,z_f}_{i,l})(1-H^{s,f}_{y,i,l})\tilde{N}^{s,z_f}_{y,i,l'} \tag{B.4}$$

The observed value of $\rho^{s,f}_{y,i,l}$ is assumed to be multinomially distributed, which leads to the following likelihood function (ignoring constants independent of the model parameters) for each of the two sources of length-frequency data:

$$L_2 = \prod_f \prod_s \prod_y \prod_i \prod_l (\hat{\rho}^{s,f}_{y,i,l})^{\omega Z^{s,f}_{y,i} \rho^{s,f}_{y,i,l}} \tag{B.5}$$

where $\omega Z^{s,f}_{y,i}$ is a factor to weight the length-frequency data relative to the other data for sex *s*, fleet *f* and time-step *i* of year *y* (the "effective sample size" for sex *s*, fleet *f* and time-step *i* of year *y*) where $Z^{s,f}_{y,i}$ is the number of animals of sex *s* caught by fleet *f* during time-step *i* of year *y* which were sized. The quantity ω is needed because the likelihood (Equation B.5) is based on the assumption that the length-frequency data are collected by means of a simple random sample from the catch. Unfortunately, using the raw data (i.e. setting $\omega = 1$ in Equation B.5) assigns too much emphasis to the length-frequency data because the sampling for length-frequency is not random and because the assumption that vulnerability is time-invariant will be violated to some extent. Downweighting the data corrects to some extent for this.

The effective sample sizes for each category of data implied by the model fit to the data can be calculated using the approach of McAllister and Ianelli (1997). The value for quantity ω can be adjusted so that the average value of $\omega Z^{s,f}_{y,i}$ equals the model-calculated effective sample size so that the input weighting for the data is consistent with the fit of the model to the data. However, care should be taken when doing this when the data types (catch-rate, catch-in-numbers, catch length-frequency) are in conflict and ω should never be set > 1.

Equations B.4 and B.5 are based on assumption that the model is fitted separately to the data by sex. However, this approach ignores any information that may be contained in the sex-ratio of the length-frequency data. Therefore, rather than fitting to the data by sex, the model can be fitted to the sex-length data, i.e.:

$$\hat{\rho}^{s,f}_{y,i,l} = \tilde{S}^{s,f}_{y,i,l}(1-\tilde{p}^{s,z_f}_{i,l})(1-H^{s,f}_{y,i,l})\tilde{N}^{s,z_f}_{y,i,l} / \sum_{s'} \sum_{l'} \tilde{S}^{s',f}_{y,i,l'}(1-\tilde{p}^{s,z_f}_{i,l})(1-H^{s,f}_{y,i,l})\tilde{N}^{s',z_f}_{y,i,l'} \tag{B.6}$$

and

$$L_2 = \prod_f \prod_s \prod_y \prod_i \prod_l (\hat{\rho}^{s,f}_{y,i,l})^{\omega^f_{y,i} Z^f_{y,i} \rho^{s,f}_{y,i,l}} \tag{B.7}$$

The summations in Equations B.4–B.6 are taken over fleet when the length-frequency data are provided for multiple fleets combined.

The length-frequency for undersized animals and spawners is included in the likelihood function analogously to the length-frequency for the landings (Equations B.4–B.7), except the model predictions are computed to match the data type. The model-predicted number of animals of sex *s* in sub-zone *z* and length-class *l* during time-step *i* of year *y* which are undersized for fleet *f* are:

$$(1-\tilde{S}^{s,f}_{y,i,l})(1-\tilde{p}^{s,z_f}_{i,l})\tilde{N}^{s,z_f}_{y,i,l} \tag{B.8a}$$

while the model-predicted number of animals of sex s in sub-zone z and length-class l during time-step i of year y that are discarded live because that are spawning is:

$$\tilde{S}^{s,f}_{y,i,l}\, \tilde{p}^{s,z_f}_{i,l}\, \tilde{N}^{s,z_f}_{y,i,l} \tag{B.8b}$$

B.3 Catch-in-number

The commercial catches in number, $C^{N,f}_{y,i}$, are assumed to be lognormally distributed about their expected values. The contribution of these data to the likelihood function is therefore given by:

$$L_3 = \prod_f \prod_y \prod_i \frac{1}{C_{y,i}^{N,f}\sqrt{2\pi}\sigma_N^f} \exp\left(-\frac{(\ell n C_{y,i}^{N,f} - \ell n \hat{C}_{y,i}^{N,f})^2}{2(\sigma_N^f)^2} \right) \tag{B.9}$$

where $\hat{C}_{y,i}^{N,f} = \sum_s \sum_l V_l^s \tilde{S}_{y,i,l}^{s,f} \tilde{N}_{y,i,l}^{s,z_f} F_{y,i}^f$.

B.4 Indices of settlement

The puerulus data are assumed to provide a relative index of settlement which is normally or lognormally distributed, i.e.:

$$L_4 = \prod_z \prod_y \frac{1}{\sqrt{2\pi}\sigma_{J,y}^z} \exp\left(-\frac{(J_y^z - \tilde{q}^z R_{y+L_R}^z)^2}{2(\sigma_{J,y}^z)^2} \right) \tag{B.10a}$$

$$L_4 = \prod_z \prod_y \frac{1}{\sqrt{2\pi}\tilde{\sigma}_{J,y}^z} \exp\left(-\frac{(\ell n J_y^z - \ell n(\tilde{q}^z R_{y+L_R^z}^z))^2}{2(\tilde{\sigma}_{J,y}^z)^2} \right) \tag{B.10b}$$

where J_y^z is the puerulus-based index of settlement for sub-zone *z* and year *y*, $\sigma_{J,y}^z$ is the standard deviation of J_y^z, $\tilde{\sigma}_{J,y}^z$ is the standard deviation of the logarithm of J_y^z, $\tilde{q}^z$ is the constant of proportionality between the puerulus-based indices of settlement for sub-zone *z* and settlement for sub-zone *z*, and L_R^z is the lag (in years) for sub-zone *z* between the puerulus stage and settlement to the first size-class considered in the model.

The maximum likelihood estimate for $\tilde{q}^z$ can be obtained analytically:

$$\hat{\tilde{q}}^z = \sum_y \frac{1}{(\sigma_{J,y}^z)^2} J_y^z R_{y+L_R^z}^z / \sum_{y'} \frac{1}{(\sigma_{J,y'}^z)^2} (J_y^z)^2 \tag{B.11a}$$

$$\hat{\tilde{q}}^z = \exp\left(\sum_y \frac{1}{(\tilde{\sigma}_{J,y}^z)^2} \ell n(J_y^z / R_{y+L_R^z}^z) / \sum_{y'} \frac{1}{(\tilde{\sigma}_{J,y'}^z)^2} \right) \tag{B.12b}$$

where $\tilde{n}^z$ is the number of years for which puerulus-based indices of settlement are available for sub-zone *z*.

B.5. Tag-recapture

Tag-recapture data provide a basis to estimate movement, growth and exploitation rates. However, within this model (and owing to uncertainty regarding, for example, reporting rates), the tag-recapture data are used only to determine growth and movement rates/

B.5.1. Using tagging data to estimate movement

Tagging data are used to estimate movement following the recapture conditional framework of McGarvey and Feenstra (2002). Specifically, the likelihood for the tag-recapture data is the product over recaptures of the probability of recapturing a tag in the sub-zone in which it was recaptured given its sub-zone of release, its time of release and the time that it was at liberty for. The recapture-conditioned recapture probability for tagged lobsters at large for just one movement time is:

$$f(z_\mathrm{r} \mid z_\mathrm{t}, t_\mathrm{t}, t_\mathrm{r}, s) = \frac{Y_{t_*}^{z_\mathrm{t}, z_\mathrm{r}} \left[\prod_{t=t_*}^{t_\mathrm{r}-1} (1 - \tilde{H}_{t,l}^{s,z_r}) e^{-Mt_t} \right] \tilde{H}_{t_\mathrm{r},l}^{s,z_\mathrm{r}}}{\sum_{z'_\mathrm{r}=1}^{n_z} Y_{t_*}^{z_\mathrm{t}, z'_\mathrm{r}} \left[\prod_{t=t_*}^{t_\mathrm{r}-1} (1 - \tilde{H}_{t,l}^{s,z'_r}) e^{-Mt_t} \right] \tilde{H}_{t_\mathrm{r},l}^{s,z'_\mathrm{r}}} \tag{B.13}$$

where z_{t} is the sub-zone of release, z_{r} is the sub-zone of recapture, t_{t} is the time when the tagged animal was released, t_{r} is the time when the tagged animal was recaptured, t_* is the time-step between release and recapture when movement occurs, and n_{z} is the number of sub-zones is the model.

For computational ease, the dependence of $\tilde{H}$ on size is dropped when evaluating Equation B.12 (e.g. vulnerability is assumed to be 1 for all tagged animals). Equation B.12 can be extended to animals that were at liberty for more than one movement time. For example, the extension to two movement times is:

$$f(z_{\mathrm{r}} \mid z_{\mathrm{t}}, t_{\mathrm{t}}, t_{\mathrm{r}}, s) = \frac{\left(\sum_{z=1}^{n_{\mathrm{z}}} Y_{t_1}^{z_{\mathrm{t}},z} \left[\prod_{t=t_1}^{t_2} (1-\tilde{H}_{t,l}^{s,z}) e^{-Mt_t}\right] Y_{t_2}^{z,z_{\mathrm{r}}}\right) \left[\prod_{t=t_2}^{t_{\mathrm{r}}-1} (1-\tilde{H}_{t,l}^{s,z_{\mathrm{r}}}) e^{-Mt_t}\right] \tilde{H}_{t_{\mathrm{r}},l}^{s,z_{\mathrm{r}}}}{\sum_{z'_{\mathrm{r}}=1}^{n_{\mathrm{z}}} \left(\sum_{z=1}^{n_{\mathrm{z}}} Y_{t_1}^{z_{\mathrm{t}},z} \left[\prod_{t=t_1}^{t_2} (1-\tilde{H}_{t,l}^{s,z}) e^{-Mt_t}\right] Y_{t_2}^{z,z'_{\mathrm{r}}}\right) \left[\prod_{t=t_2}^{t_{\mathrm{r}}-1} (1-\tilde{H}_{t,l}^{s,z'_{\mathrm{r}}}) e^{-Mt_t}\right] \tilde{H}_{t_{\mathrm{r}},l}^{s,z'_{\mathrm{r}}}}$$

where t_1 is the time when movement first occurs after tagging, and t_2 is the time when movement occurs before recapture.

Generalization to tagged animals which were at liberty for more than two movement periods is straightforward and involves accounting for all possible paths between the sub-zone of release and that of recapture.

B.5.2 Using tagging data to estimate growth

After assigning the tagging data to sub-zone, sex, size-class and time-step of release, the tag-recapture data can be summarized by the vectors (l_1, t_1, *t* and l_2, where l_1 is the size-class-at-release, t_1 is the time-step at release. *t* is the time-at-liberty [in model time-steps], and l_2 is the size-class-at-recapture). The contribution of the tag-recapture data for one animal to the likelihood function is the probability of observing that an animal tagged at the start of time-step t_1 when it was in size-class l_1 and at liberty for *t* time-steps, was recaptured when it was in size-class l_2 (McGarvey and Freenstra, 2001; Punt *et al.*, 2009). This probability is the (l_1, l_2) entry of the matrix given by $L_4 = \prod_{i=t_1}^{t_1+t-1} \mathbf{X}_i^{s,z}$. The contribution of the data on growth to the likelihood function is then the product of L_4 over all of recaptured animals. The data used to estimate growth are restricted to animals which did not change sub-zones between release and recapture so that the growth estimates pertain to a single sub-zone. The likelihood function for the growth data allows for random sizing error (i.e. the recapture size-class is incorrect with probability α).

3 Parameter estimation

Table 2 lists the parameters of the population dynamics model and the objective function, and highlights those parameters assumed to be known exactly and those parameters whose values are estimated by fitting the model to the data (many parameters can either be estimated or pre-specified).

C.1. Movement

The parameters that determine movement can either be pre-specified or estimated. The movement parameters are specified in logit-space, i.e. for two regions:

$$Y_i^{s,z,z'} = e^{\tau_i^{s,z,z'}}; \quad Y_i^{s,z',z} = 1/(1+e^{\tau_i^{s,z,z'}}) \tag{C.1}$$

where $\tau_i^{s,z,z'}$ the parameter which determines the movement rate among sub-zones. $\tau_i^{s,z,z'}$ may be sex-specific or independent of sex.

C.2 Modelling growth

The size-transition matrix **X** for a given year can either be pre-specified or computed using the equation:

$$X_{l',l,i}^{s,z} = \begin{cases} \displaystyle\int_{-\infty}^{L_1+\Delta L^s/2} \frac{1}{\sqrt{2\pi}} e^{-(L-E(L_{l'})_i^{s,z})/(2(\sigma(L)_i^{s,z})^2)} dL & \text{if } l=1 \\ \displaystyle\int_{L_l+\Delta L^s/2}^{L_l+\Delta L^s/2} \frac{1}{\sqrt{2\pi}} e^{-(L-E(L_{l'})_i^{s,z})/(2(\sigma(L)_i^{s,z})^2)} dL & \text{if } 2 \le l \le n_L^s - 1 \\ 1 - \displaystyle\int_{-\infty}^{L_n-\Delta L^s/2} \frac{1}{\sqrt{2\pi}} e^{-(L-E(L_{l'})_i^{s,z})/(2(\sigma(L)_i^{s,z})^2)} dL & \text{if } l = n_L^s \end{cases} \qquad \text{(C.2)}$$

where $E(L)_i^{s,z}$ is the expected length of an animal of sex *s* and length *L* in sub-zone *z* after growth occurs during time-step *i*, and

$\sigma(L)_i^{s,z}$ is the standard deviation of the length of an animal of sex *s* and length *L* in sub-zone z after growth occurs during time-step *i*.

Two options exist to parameterize $E(L)_i^{s,z}$ and $\sigma(L)_i^{s,z}$.

A. The von Bertalanffy parameterization assumes that the growth increment follows a von Bertalanffy growth curve, i.e. $E(L)_i^{s,z} = L - (\ell_\infty^{s,z} - L)(1 - e^{-\kappa_i^{s,z}})$, while the standard deviation of the growth increment, $\sigma(L)_i^{s,z}$, depends on time-step, sex, and sub-zone but not size, i.e. $\sigma(L)_i^{s,z} = \sigma_i^{s,z}$.

B. The polynomial parametersization is based on setting $E(L)_i^{s,z}$ and $\sigma(L)_i^{s,z}$ using polynomial functions, i.e.:

$$E(L)_i^{s,z} = \sum_{j=0}^{m_i^{s,z}} L^j \delta_{i,j}^{s,z} \; ; \qquad \sigma(L)_i^{s,z} = \sum_{j=0}^{\tilde{m}_i^{s,z}} L^j \tilde{\delta}_{i,j}^{s,z} \qquad \text{(C.3)}$$

where $\ell_\infty^{s,z}$, $\kappa_i^{s,z}$, and $\sigma_i^{s,z}$ (von Bertalanffy parameterization), and $\delta_{i,j}^{s,z}$ and $\tilde{\delta}_{i,j}^{s,z}$ (polynomial parameterization) are the parameters which determine the size-transition matrix. The number of terms in the polynomial model are defined by the quantities $m_i^{s,z}$ and $\tilde{m}_i^{s,z}$.

The values for the parameters $\ell_\infty^{s,z}$, $\kappa_i^{s,z}$, and $\sigma_i^{s,z}$ may change over time (separate estimated parameters for blocks of years) or change as a function of a covariate, e.g. $\ell_{\infty,y}^{s,z} = \overline{\ell}_\infty^{s,z} e^{\phi_y^{s,z} E_y}$ where $\overline{\ell}_\infty^{s,z}$ is a reference value for $\ell_\infty^{s,z}$, E_y is the value of the covariate, and $\phi_y^{s,z}$ is the parameter which relates changes in the covariate to changes in $\ell_\infty^{s,z}$.

C.3. Vulnerability

Vulnerability-at-length for each fleet can either be pre-specified or estimated. When vulnerability is estimated, each vulnerability-at-length within a pre-specified range of lengths can be treated as an estimable parameter, or vulnerability can be treated as an (estimable) logistic function of length. Vulnerability for a fleet can be sex-specific or independent of sex and vulnerability for one fleet can be assumed to be same as that for another fleet. Vulnerability can change over time in "blocks"

C.4 Bayesian considerations

It is necessary to specify prior distributions for all of the estimable parameters of the model (Table 2) if Bayesian methods are to be used to represent uncertainty. The prior assumed for the logarithm of mean settlement is $U(-\infty,\infty)$, with the intention that this prior is "uninformative". It should be noted, however, that no prior can be truly "uninformative" because a prior that is uninformative for one quantity in a model will be informative about some other quantity in that model (Punt and Hilborn, 1997). The prior for each of the settlement residuals is $N(0;\sigma_R^2)$, i.e. the contributions of the settlement t residuals to the objective function is:

$$P = 0.5\sum_z \sum_y (\varepsilon_y^z)^2 / (\sigma_{R,y}^2) \tag{C.4}$$

It is also possible to impose a penalty which relates the settlement residuals to environmental variables, i.e.:

$$P = 0.5\sum_z \sum_y (\hat{q}^z \varepsilon_y^z - E_y^z)^2 / \sigma_{E,z}^2 \tag{C.5}$$

where $\hat{q}^z$ is a parameter which relates the settlement residuals for sub-zone z with the environmental index for that zone, and $\sigma_{E,z}$ determines the strength of the relationship between the environmental index and the settlement residuals.

The Markov Chain Monte Carlo method (Hastings, 1970; Gelman *et al*., 1995) is used to develop the posterior distributions. The MCMC method was chosen over alternative methods such as the Sample-Importance-Resample method (Rubin, 1987) because it works well with the complicated posterior surfaces commonly encountered when applying size-structured models (Punt and Hilborn, 1997). A major problem associated with the application of Bayesian methods to complex problems is how to assess whether convergence to the posterior has occurred (Punt and Hilborn, 1997). In this study, this assessment has been achieved by in four ways.

a) Visually examining the traces for several of the key model outputs.
b) Computing the diagnostic statistics developed by Raftery and Lewis (1992), Geweke (1992), and Heidelberger and Welsh (1983).
c) Computing the so-called “single chain Gelman statistic”. This statistic involves comparing the variability of the means in 50 segments of the chain with the variability within each such segment.
d) Examining the partial auto-correlation function to assess whether the amount of thinning is sufficient to ensure that sequential points are essentially uncorrelated.

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Table 1. The data inputs for the model. Data for the "required" data sources are not needed for all combinations of year, time-step and sub-zone.

Quantity	Description	Required / Optional
C_t^f	Catch by fleet *f* during time-step *i* of year *y* (in mass)	Required *
$LML_y^{s,z}$	The legal minimum size for sex *s* and sub-zone *z* during year *y*	Required *
$I_{y,i}^f$	Catch-rate index for time-step *i* of year *y* and fleet *f*	Required [&]
$\rho_{y,i,l}^{s,f}$	Fraction of the catch of animals of sex *s* in number during time-step *i* of year *y* fleet *f* that are in size-class *l*	Required [&]
$\omega_{y,i}^{s,f}$	"Effective sample size" for sex *s*, fleet *f*, and time-step *i* of year *y*	Required [$]
$C_{y,i}^{N,f}$	Catch by fleet *f* during time-step *i* of year *y* (in numbers)	Optional
J_y^z	The puerulus-based index of settlement for sub-zone *z* and year *y*	Optional
L_R^z	The lag (in years) between the puerulus stage and settlement to the first size-class considered in the model for sub-zone *z*	Optional
$T_{y,i,l}^{s,z}$	The number of tagged animals of sex *s* in size-class *l* released in sub-zone *z* during time-step *i* of year *y*	Optional
$\tilde{T}_{y,i,l}^{s,z}$	The number of tagged animals of sex *s* in size-class *l* recaptured in sub-zone *z* during time-step *i* of year *y*	Optional
E_y^j	jth Environmental covariate	Optional

* Required for all years, time-steps and sub-zones.

& Not required for all years and time-steps but performance increases with additional data.

$ Required for the years and time-steps for which size-composition data are provided.

Table 2. Parameters of the model and their prior distributions. Parameter values fixed using auxiliary information are denoted as "User-specified".

Parameter	Description	Prior distribution
ε_y^z	The settlement residuals	$N(0;\sigma_R^2)$
$\ell\text{n}(\overline{R}^z)$	Mean settlement	U(-∞, ∞)
$\ell\text{n}(R_0^z)$	Unfished settlement	U(-∞, ∞)
h	Steepness	U[0.2, 1]
$\tilde{\sigma}_R$	The extent of variation in settlement for years after y_{start}	User-specified
$\tilde{\tau}$	The extent to which σ_R changes with time	User-specified
$X_{l',l,y,i}^{s,z}$	Fraction of the animals of sex *s* in size-class *l'* in sub-zone *z* that grow into size-class *l* at the end of time-step *i* and year *y*	User-specified *
$\tau_i^{s,z,z'}$	Parameter which determines the fraction of the animals of sex *s* that move from sub-zone *z'* to sub-zone *z* at the end of time-step *i*,	User-specified *
M	Natural mortality	User-specified
$S_{y,l}^{s,f,\text{O}}$	Vulnerability as a function of sex and length	User-specified *
$P_{i,l}^s$	The proportion of animals of sex *s* in size-class *l* which are spawning during time-step *i*	User-specified
$\tilde{H}_l^{s,f}$	The relative vulnerability of an animal of sex *s* in size-class *l* to be being high-graded by fleet *f*	User-specified
$\tilde{H}_y^f$	the impact of high-grading by fleet *f* during year *y*	Calculated
$\Omega_i^{s,z}$	Fraction of the settlement by time-step, sex and sub-zone	User-specified *
Φ_l^s	Proportion of the settlement of animals of sex *s* that occurs to size-class *l*	User-specified
Q_l^z	Egg production as a function of size and sub-zone	User-specified
$W_l^{s,z}$	Mass as a function of size, sex, and sub-zone	User-specified
i_{m}	The time-step in which spawning occurs	User-specified
L_l^s	The lower limit of size-class *l* for sex *s*	User-specified
$\ell_\infty^{s,z},\kappa_i^{s,z},\sigma_i^{s,z}$	Von Bertalanffy growth parameters	User-specified *
$\delta_{i,j}^{s,z},\tilde{\delta}_{i,j}^{s,z}$	Polynomial growth parameters	User-specified *
$\phi_y^{s,z}$	Link between growth parameters and environmental data	User-specified *
α	Probability is incorrectly assigning a recaptured animal to a size-class	User-specified *
χ, ω	Parameters which define the initial state	User-specified
$\ell\text{n}q_i^z$ / $\ell\text{n}\tilde{\tilde{q}}_i^z$ / $\ell\text{n}\tilde{q}^z$, $\ell\text{n}\hat{q}^z$	Catchability	U(-∞, ∞)
$\theta_i^{f,j}$	Parameters linking environmental variables and catchability	User-specified *
$\sigma_{q,y,i}^z$ / $\tilde{\tilde{\sigma}}_{q,y,i}^z$	Standard deviation of the random fluctuations in catchability for sub-zone *z* and time-step *i* of year *y*	User-specified * &
σ_N	Standard deviation of the random fluctuations in mean mass	User-specified *
$\sigma_{J,y}^z$ / $\tilde{\sigma}_{J,y}^z$	The standard deviation / *CV* of J_y^z	User-specified * &

* Indicates parameters that could be estimated or pre-specified.

& If estimated, only a single value can be estimated for each index. Also, the same value can be estimated for multiple catch-rate series.

User Manual: ROCK23A

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This document outlines how to specify the values included in the input files for ROCK23A (GENERAL.ROC, NORTH.DAT, NORTH.CTL and ROCK23A.PIN)[1]. It does not detail the mathematical specifications for the model or for the method used for parameter estimation. These are available in a separate document. Similarly, the mathematical specifications and user manual for the projection software are described elsewhere. The appendix provides a glossary of key terms.

A. Specification of the data

The data are specified in the file "NORTH.DAT".

A.1 Stock and dimensions

The inputs in this section are:

(a) the first and last years of the assessment period (these are the years for which data are available – the modelled period will be longer than this, depending on the number of the length of burn-in period),
(b) the number of years the model is "burnt-in" to set up the initial size-structure (this should be approximately the number of age-classes in the population),
(c) the number of years for which fishing mortality should be set to zero before the start of the burn-in (this value should be 1 if there is only one area and larger than this (10−15 years) if there are multiple areas or "settlement" is computed from a stock-recruitment relationship; see Section B.4c for specifying a stock-recruitment relationship,
(d) the number time-steps during each year (1 for an annual model; 2+ for a model with multiple periods during the year; note that each time-step can be of a different duration),
(e) the total number of sub-zones for which data are supplied (this number needs to be as large as the number of sub-zones that are to be assessed; giving data for more sub-zones than are to be assessed simplifies model specification and running of sensitivity tests),
(f) the number of sub-zones actually assessed (this number must be at least 1),
(g) the number of MPAs (zero is there are no MPAs; 1+ otherwise; if this input is specified it is necessary to indicate when the MPAs were established (Section A.3), the size of the MPA relative to the sub-zone in which it is located (Section B.5) and movement between the fished areas and the MPAs; (Section B.6b)),
(h) the number of fishery fleets (at least 1),
(i) the number of survey fleets (0 if there are no survey fleets),
(j) a list of indexes for the data sub-zones to indicate which are the actual sub-zones on which the assessment is to be based (there should be one value for each sub-zone for which data are available; the value should be zero or negative if the sub-zone concerned is to be ignored and a number from 1 to the number of assessed sub-zones otherwise; this determines which sub-zones are to be used in the analysis under consideration),
(k) a list of indexes for each fishery fleet (the value should the number of the area in which the fleet operates; there must be one value for each fishery fleet),
(l) a list of indexes for each survey fleet (the value should the number of the area in which the fleet operates; there must be one value for each fishery fleer; blank if there are no survey fleets),
(m) a value for each fishery fleet indicating whether the catch is reported in weight (1) or in numbers (2) (fishery fleets only; the catches by the survey fleets are assumed to be negligible), and
(n) a value for each sub-zone indicating the major commercial fleet in the sub-zone.

---

[1] To run the model, ROCK23A.TPL must be compiled to an .EXE file using AD Model Builder. To run the ROCK23A.EXE, open a windows command prompt (cmd.exe) in the folder in which the input files are located, type ROCK23A and press enter

Note that each of the items a-n (except l) must have at least one value associated with it. The example below involves eight fleets (five fishery fleets and three survey fleets) and three sub-zones, only two of which (the first and third) are actually being assessed.

```
1983                    # First year of the assessment
2006                    # Last year of the assessment
20             # Number of burn-in years
10             # Years for which F is zero
9                       # Time steps per year
3                       # Number of sub-zones with data
2                       # Total number of sub-zones to be assessed
0                       # Number of MPAs
5                       # Number of fishery fleets
3                       # Number of survey fleets
1 -1 2                  # Indexes between data and actual areas
1 1 2 2 3               # Indexes between fishery fleets and sub-zones
1 2 3                   # Indexes between survey fleets and sub-zones
1 1 2 1 1               # Are the catches in weight (1) or numbers (2)
1 3 5                   # The major commercial fleets by sub-zone
```

A.2 Biological processes

The model is flexible in terms of which biological processes are to be modelled. The biological processes currently included in the model (and their codes) are listed below. The model executes the specified biological process in the order input for each time-step (note that it is not necessary to include all of these biological processes in every application of the model; for example, analyses based on a single sub-zone and no MPAs won't need processes 1 and 2).

1. Move animals among sub-zones (if movement is specified to occur during the current time-step)
2. Create new MPAs (if any new MPAs are specified to occur during the current time-step)
3. Compute the egg production.
4. Remove half of natural mortality.
5. Compute the exploitation rate.
6. Compute the reference biomass.
7. Remove the catch.
8. Implement growth among size-classes (only used if growth occurs during the current time-step).
9. Add "settlement" to the modelled population (reminder: the term "recruitment" is used in this manual when referring to growth larger than the minimum legal size and entering the exploitable biomass, and "settlement" when referring to entering the modelled population, which will include animals smaller than the minimum legal size).
10. Compute the total legal biomass.

The order of some of the processes should not be changed. For example, the exploitation rate must be calculated before the catch is removed. However, depending on the order of inputs, growth can, for example, be specified to occur before or after the catch is removed. An example case is given below. Note that the first input is the number of processes that may occur in each time-step and that not mentioning a process will lead to it being ignored (all models should minimally remove natural mortality and catch, compute exploitation rates, and allow for growth and settlement).

```
11 # Number of biological processes
1 # Move animals among sub-zones
2 # Create new MPAs
3 # Compute egg production
4 # Remove half of mortality
5 # Compute exploitation rates
6 # Compute reference biomass
10 # Compute total-legal biomass
7 # Remove catch
4 # Remove half of mortality
8 # Allow for growth
9 # Allow for settlement
```

The final inputs in this section are: (a) the time-step when egg production should be computed, and (b) the first time-step for which "settlement" for a given year relates to (for example, if there are 9 time-steps and this input is 5, then "settlement" for time-steps 1−4 is based on the "settlement" for year *y* while "settlement" for time-steps 5−9 is based on the settlement for year *y*+1).

```
1                # Time-step in which spawning occurs
8                # Time-step for calculating settlement
```

Note that if the model only has one time-step both of these inputs must be set to 1.

A.3 Specifications for MPAs

The specifications for when each MPA was implemented and in which assessed sub-zone each MPA falls is specified as follows:

```
1990 2 1          # Year started, Time started, MPA Home
```

This line implies that an MPA was started in 1990 (i) in the second time-step (ii) and it is located in assessed sub-zone 1 (iii). Note that no values should be supplied for this input (the line is left blank) if no MPAs are specified (see Section A.1g above).

A.4 Specifications for size-classes

A.4a Number of sizes size-classes

The lower limit of the first size-class (assumed to be the same for both sexes) is entered (i), followed the number of size-classes for males (ii) and females (iii), i.e. for the example below the first size-class starts at 82.5mm, there are 29 size-classes for males and 21 for females.

```
82.5                     # Start of lowest size-class
29 21                    # Number of size-classes (males then females)
```

A.4b Size-class widths

"1" is entered to indicate that the width of each size-class is the same and "2" for variable-length size-classes. If the width of each size-class is the same then the specification for the number of size-class is given as males (4 mm in this example) and then females (5 mm in this example):

```
1                        # Set to 1 for fixed size-classes
4 5                      # Widths of length-classes (males then female)
```

Alternatively, if the size-class width differs among size-classes, the entire sequence of size-limits (upper values) must be provided for males (one row) and females (next row):

```
2                        # Set to 2 for variable-length size-classes
90 100 120 130           # Males
90 105 110 120           # Females
```

A.5 Specifications for reference size and recruitment

The software outputs a variety of biomasses. The "reference" biomass is the total biomass (males+females) above the "reference size" and is useful for comparisons among, for example, different states. The "reference size" is entered here (one value for each assessed area) (a), along with time-step during which recruitment to the fishery is calculated (b) (if there are 9 time-steps and this input is 5, then the reported recruitment for year *y* is the number of animals growing to above the minimum legal size during time-steps 5−9 of year y^{-1} and during time-steps 1−4 during year *y*). The time-step for defining recruitment should be "1" for an annual model. Note that this input does not specify when animals are added to the model (see Section B.7b for this).

```
# Output statistics
80 80            # Reference size (one value for each assessed area)
8                # Time-step for calculating recruitment to the LML
```

Note that the time-steps which define when recruitment is calculated (this input) and when “settlement” occurs (see Section A.2) need not be the same. Setting these inputs to different values will lead to recruitment consisting of animals which grow to size-classes above the LML based on two values for the annual “settlement”.

A.6 Catch data

The catch data for each time-step are provided in rows. There must be a row for each time-step between the first time-step of the first year to the last time-step of the last year (even if the catch was zero for the entire time step).

A.6a Landings

The first catch input is the landings (although it can be the total catch if landings and discards are not to be modelled separately). The values in each row are the year, the time-step, and the catches for each fleet for which data are provided. For example, the catch data for a model with two annual time-steps and four fleets would be entered as:

```
# Catch data
# ==========
# Year Time-step Fleet-1 Fleet-2 Fleet-3 Fleet 4
  1978         1     100     200       0     100
  1978         2     110     190       0     100
  1979         1     120     180     100     100
```

A.6b Dead discards

“1” is specified if there are data on “dead discards” (i.e. assuming the catches entered as live animals) [“0” otherwise]. This input is then followed by the proportion of the landed [live] catch which is discarded dead if “1” was entered (no input is provided if there are no “dead discards”). Note that discard rates must be specified for all years and time-steps within the year. For example, if there are two fleets and fleet 1 has dead discards but fleet 2 does not, the input would be

```
# Discard rates
# =============
1              # Set to 1 if there are dead discards; 0 otherwise
# Year Time-step Fleet-1 Fleet-2
  1978         1     0.1     0.0
  1978         2     0.1     0.0
  1979         1     0.1     0.0
```

A.6c High-grading

The next input is “1” is there are data on the faction of the legal catch which is released live (i.e. high-grading) [“0” otherwise]. This input is then followed by the proportion of the landed [live] catch which is discarded live if “1” was entered (no input is provided if there are no discards). Note that high-grade rates must be specified for all years and time-steps within the year. It is necessary to indicate that high-grading is occurring when specifying vulnerability patterns (see Section B.8a) if “1” is entered at this input. For example, if there are two fleets and fleet 1 high grades but fleet 2 does not, the input would be

```
# High-grade fractions
# ====================
1              # Set to 1 if there is high-grading; 0 otherwise
# Year Time-step Fleet-1 Fleet-2
  1978         1     0.1     0.0
  1978         2     0.1     0.0
  1979         1     0.1     0.0
```

A.7 Catch-rate data

A.7a General specifications

Catch-rate data pertain to fleets (and hence sub-zones because each fleet is linked to a single sub-zone). The input in this section are:

(i) the number of catch-rate series that will be used (this will be less than the number of catch-rate series entered if data are specified for fleets which are found in sub-zones which are not to be assessed during the current model run).

(ii) how many residual standard deviations are to be estimated and how many are to be shared. There are 29 catch-rate series in the case below, but only 15 residual standard deviations ("sigmas") are estimated because some are shared (e.g., the same residual standard deviation applies to catch-rate series 1 and 8). If the value at this input for a catch-rate series is set to 0, the assessment assumes that the residual standard deviation (by year) for that catch-rate series is known *a priori*, and is set to the values entered in the final set of inputs in this section.

(iii) How many catchability parameters should be assumed to be the same? In the example below catchability is assumed to be the same for series 1, 2 and 3 .

```
# Catch rate data
# ===============
29                                      # Number of CPUE series
# Treatment of Sigma (0 pre-specify; otherwise CPUE group number of estimated
sigma)
1 2 3 4 5 6 7 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 9 10 11 12 13 14 15
# Treatment of catchability
1 1 1 4 5 6 7 8 9 10 11 12 13 14 15 16 …
```

A.7b Relating catchability to environmental variables

This set of inputs specify how (if at all) catchability is related to an environmental index [or a forcing function in general]. The inputs are (i) the number of environmental time-series catchability is related to (0 means none), followed by (ii) specifications for which environmental indices are related to catchability. The latter two inputs are first the index of the environmental variable concerned (see Section B.2 for how to input environmental variables), and then a number to indicate the parameter which will be used to link catchability to the variable concerned. Note that the index of the catch-rate series must be entered before specifying the indices for environmental indices for checking purposes. In the example below there are two catch-rate series, the first series is not related to any environmental indices and the second (hence the "2" at the start of the second line) is related to three such indices (numbers 5, 7 and 9), and the value of the parameter linking catchability to the environmental variables is the same for environmental variables 7 and 9 (it is both parameter 2).

```
0 3                 # Number of environmental indices by CPUE series
2 5 1 7 2 9 2       # Cpue Series No; environmental series numbers
```

Note that if you want to specify that catchability is increasing exponentially at 5% per annum, you should create an "environmental index" with values 0, 0.04879, 0.09531, 0.139762, etc. These are the logged values for catchabilities of 1, 1.05, 1.10, ... The parameter associated with this index (see Sections B.9 and D.k) would be set to 1 and not estimated.

A.7c Further inputs

(i) The minimum residual standard deviation (often referred to as "sigma") (this value should be set to a value larger than zero to avoid overweighting a short catch-rate series; although the same objective can often be achieved by assuming that the residual standard deviation for a short catch-rate series equals that for another catch-rate series),

(ii) the number of types of catch-rate series ("1" if there are commercial catch-rate data only, or "2" if there are commercial catch-rate data and FIMS data),

(iii) the phase in which the FIMS catchability coefficients should be estimated (only provided, i.e. leave blank, if "2" was entered at the previous input),

(iv) the number of data points to be entered, and

(v) the number of data points that will be used (this number and that at the previous input will differ if data are provided for more fleets than are to be included in the assessment).

The value for this last input determines the amount of storage for the catch-rate data. Its value need not be identical to the number of data points to be used in the assessment, but must be no less than this (setting the number of "used" data points to a value higher than necessary will increase the storage requirements of the analysis somewhat).

```
0.04                                    # Minimum sigma
2                   # Number of CPUE types
2                   # Phase for FIMS q
342                                     # Number of data points
219                                     # Number that will be used
```

A.7d The data

The final inputs for this section are the data themselves (ordered by (i) CPUE series, (ii) fleet, (iv) year and (v) time-step). The "Type" (vi) is "1" for commercial catch-rate data and "2" for FIMS data, while the "Source" (iii) is "1" for catch-rate data and "2" for pre-recruitment indices. Note that allowance can also be made for (pre-specified) rates of change in catchability (See Section B.7). Multiple series can be supplied for each fleet-time-step combination to allow different values for catchability to be estimated to different time-periods (e.g. due changes in regulations).

```
# Series Fleet Source Year Time-step Type   CPUE CV
   1      1         1 1983         1    1  0.768  1
   1      1         1 1984         1    1  0.801  1
   1      1         1 1983         1    1  0.768  1
   1      2         1 1985         1    1  5.978  1
```

The CV entered here (vii) is treated as a relative CV if a residual standard deviation is estimated for the catch-rate series (if a value of 1 or larger is entered at the "treatment of sigma" input for that series; see Section A.7a-ii above) or as the actual CV if a value of 0 is entered at the "treatment of sigma" input for that series). If there is more than one CPUE series for each fleet-time-step combination, the first of these should be entered as above and the remaining indices should be entered as data from 'virtual' survey fleets (where vulnerability for these fleets is assumed to be identical to that for the original fleet; See Section B.8a-i). Each fleet-time-step combination should be assigned a survey fleet number which would only be used for specifying the catch rates (and must be allocated and linked to the sub-zone in Section A.1).

A.8 Catches-in-numbers data

A.8a General specifications

The inputs for catch-in-numbers data are essentially identical to those for catch-rate data (except that there is no FIMS analogy for catch-in-numbers and there is no catchability so no link to environmental variables):

(i) the number of catch-in-numbers series that will be used.

(ii) how many residual standard deviations are to be estimated and how many are to be shared. If the value for a catch-in-numbers series is set to 0, the assessment assumes that the residual standard deviations (by year) for that catch-in-numbers series are known *a priori*, and are set to the values entered in the final set of inputs in this section. A residual standard error is estimated for numbers 1 and larger.

(iii) the minimum residual standard deviation (this value should be set to a value larger than zero to avoid overweighting a short catch-in-numbers series),

(iv) the number of data points (rows of data) to be entered, and

(v) the number of data points that will be used (these two numbers will differ if data are provided for more sub-zones than are to be assessed).

```
# Catch-in-numbers data
# ====================
2         # Number of catch-in-number series
1 2       # Treatment of Sigma (0 pre-specify;
               otherwise catch-in-numbers group number of estimated sigma)
0.04      # Minimum sigma
342       # Number of data points
342       # Number that will be used
```

A.8b The data

The final inputs for this section are the data themselves (ordered by type (category) (i), fleet (ii), catch series number [see Section A.6] (ii), time-step (iv) and year (v):

```
# Category Fleet   Year Time-step Catch-in-numbers CV
         1     1   1983         1             1200  1
         1     1   1984         1             1100  1
         1     1   1985         1             1260  1
         1     1   1986         1             1400  1
```

The category determines type of data. Available categories are: 1 – the landed catch; 2 – the discards of spawners; and 3 – the catch of under-sized animals.

A.9 Length-frequency data

Length frequency data can be supplied by fleet or for two fleets combined (fleet-combined length-frequency data would arise if a fleet fished in two sub-zones, but where some of the catches which were sized were within the sub-zones is unknown – this can occur if catch sampling data are based on factory sampling).

The inputs that determine the length-frequency information for each type of length-frequency data (by fleet or two fleets combined) include two rows of six values that specify the number of vectors of length-frequency samples. The six values listed are the numbers of length-frequency samples for: (I) male-commercial, (II) female-commercial, (III) male+female-commercial, (IV) male-research, (V) female-research, and (VI) male+female-research. The two rows list respectively (i) the number of samples for which data are provided and (ii) the number of samples which will be actually be used. The values for this last input determine the amount of storage for the length-frequency data. These values need not be identical to the number of data points to be used in the assessment, but must be no less than this.

```
# sample sizes
0 0 0 0 0 227             # Number of data points
0 0 0 0 0 227             # Number that will be used
```

A.9a Minimum length-frequency sample size

This input indicates the minimum sample size for inclusion in the analyses. If the sample size for a year's length-frequency data is less than this value, the data for that year are ignored.

```
50 # Minimum sample size
```

A.9b Data for individual fleets

Each line of length-frequency data includes type (category) (i.e. male-commercial; female-commercial; male+female-commercial; male-research; female- research; male+female-research), fleet, time-step and year, and sample size (the total number of sized animals, and the data for each size class specified for males and then females)).

```
# Males+Females -- Research (Pot sampling)
# Category Fleet Time-step Year Sample Size The data
         1     1         2  1978        120   72  89  90  100  …
         1     1         3  1978        200  172 819  91  100  …
         1     1         4  1978        200  272 890  90  102  …
```

The category column specifies the type of length-frequency (1=landed catch; 2=released spawners; 3=high-graded animals). Note that the vulnerability pattern for a fleet (see Section B.8a) needs to allow for release of spawners and high-grading if data for spawners and high-graded animals are to be fit to for that fleet.

A.9c Combined fleets

There are two additional inputs for fleet-combined length frequency data which are provided before the combined-fleet length-frequency data themselves (which are formatted as in Section A.9b). These are the number of combinations of fleets ("3" in the example below) and then a line for each fleet combination which lists the code for the fleet combination (in this case 26, 27, and 28) for which data will be specified and the original model fleets (i.e. fleet "26" relates to the fleet-combined length-frequency data for fleets 6 and 9 combined).

```
# Length-frequency data (fleet combined)
# ====================================
3 # number of fleet-combinations
26 6 9
27 7 10
28 8 11
```

This is followed by a block of sample sizes as above (two rows, six columns), which must be provided, even if no combined-fleets are used. For example

```
# sample sizes
0 0 0 0 0 227             # Number of data points
0 0 0 0 0 227             # Number that will be used
```

Or if no combined fleets are used:

```
# sample sizes
0 0 0 0 0 0            # Number of data points
0 0 0 0 0 0            # Number that will be used
```

If any data are provided in this section (i.e. fleet combinations exist and the previous sample sizes were non-zero) the data are then provided in the same format as for the length-frequency data which is for a single fleet.

```
# Males+Females -- Research (Pot sampling)
# Category Fleet Time-step Year Sample Size The data
         1    26         2  1978        120   72  89  90  100 …
         1    26         3  1978        200  172 819  91  100 …
         1    26         4  1978        200  272 890  90  102 …
```

A.10 Puerulus settlement indices

The inputs for the puerulus indices are:

(a) the form of the likelihood to be assumed for the puerulus index data (0 for log-normal; 1 for normal),
(b) the number of years between the puerulus stage and entry into the lowest size-class considered in the model,
(c) the number of data points (a value of 0 here means there is no puerulus index data), and
(d) the data themselves (if 0 was not entered at the previous input). The form of the data for each year are: (i) year, (ii) puerulus index, and (iii) the standard deviation of the puerulus index

```
0                        # Likelihood component for puerulus data
3                        # Delay to entry to the model
2                        # Number of data points
# Data (Year, puerulus index, SD)
1988    21 1.23
1989    22 2.33
```

A.11 Projection phase

The inputs provided at this input provide the basis for the projections into the future. These inputs are the series for which catchability coefficients are to be output (there must be one for each time-step) – these catchability coefficients will be used to calculate effort in the future given catch and population size. One catchability coefficient needs to be entered for each time-step and sub-zone even if there is no CPUE index for some time-step/sub-zone combinations. In the example below there is no CPUE index for time-step 8 but “23” has been entered to match the specification for time-step 7. The value specified for missing CPUE series will be inconsequential if there are no future catches during the time-step for CPUE series are missing.

```
# Catchability coefficients for the future
17 18 19 20 21 22 23 23  # Catchability coefficients for the future
```

A.12 Mark-recapture data (movement)

The specifications for the mark-recapture data which are intended to inform movement are:

(a) the number of mark-recapture records (a 0 here indicates there are no mark-recapture data),
(b) the minimum time-at-liberty (in years) – a value must be provided even if there no mark-recapture data (records are ignored if the time-at-liberty is less than the minimum time-at-liberty), and
(c) the data themselves. The data for each recapture is the tag ID (not used) (i), sex (ii), year and time-step of release (iii), year and time-step of recapture (iv), sub-zone of release (v) and sub-zone of recapture (vi).

```
2939                         # Number of records:
1.0                      # Minimum time-at-liberty (years)
#              Release        Recapture     Release Recapture
#Tag No Sex Year Time-step  Year Time-step Sub-zone  Sub-zone
      1   2  1992        9  1995         1    1         1
      9   1  1992        9  1994         1    1         1
     14   1  1992        9  1994         1    1         1
     24   1  1992        9  1994         3    1         2
```

A.13 Mark-recapture data (growth)

The specifications for the mark-recapture data which are intended to inform growth are:

(a) the number of mark-recapture records,
(b) the maximum time-at-liberty (in time-steps), – a value must be provided even if there no mark-recapture data (records are ignored if the time-at-liberty is larger than the maximum time-at-liberty), and
(c) the data themselves. The data for each recapture are: sub-zone of release (and recapture) (i), sex (ii), period of release (iii), number of periods at liberty (iv), size-class of released animals (v), size-class of recaptured animals (iv), and number of animals with this set of values (vii). It is not recommended that animals which were recaptured in different sub-areas from where they were released be included in this data set (unless growth is assumed to be the same in both sub-areas).

```
29                           # Number of records:
7.0                          # Maximum time-at-liberty (time-steps)
# Sub-zone Sex RelPer PerOut RelLen RecLen   No
         1   1      1      1      1      1    5
         1   1      1      2      1      2    1
         1   1      1      1      1      2    2
```

A.14 Concluding input

The final input is a test number. This input is used to check that the input has been correctly specified. This is extremely important because an error in the input file could result in large portions of the input data being interpreted incorrectly.

```
# Test Number
123456
```

The input is echoed to two output files (CHECK.OUT and SOUTH.DAT). These files should be examined to ensure that the input has been entered correctly.

B. Specification of the control (estimation) parameters

The specifications for the estimable parameters and the likelihood function are given in the file NORTH.CTL.

B.1 Time-blocks

The first input in the CTL file specifies which time-blocks will be used in the analyses (time-blocks are one way for vulnerability and growth to change over time; see Sections B.7 and B.8). The time-blocking in the model is defined by:

(a) the number of time-block options that are to be used (“0” is there are no time blocks),
(b) the number of time-blocks for each option (in the example below there are three time-block options, two of which consist of two time-blocks [1+ number specified], and one of which consists of three time-blocks), and
(c) the years which define each of the time-blocks.

```
3                          # Number of time-block options
1 2 1                      # No of time-blocks per time-block options
1990 2000                  # Time block 1
1990 2000 2001 2003        # Time Block 2-3
1990 2001                  # Time Block 4
```

B.2 Environmental time-series

It is possible to relate some of the parameters of the model to an environmental variable such as temperature (currently only catchability and growth; see Sections A.7b and B.7b). Environmental variables are specified by (a) the number of environmental indices, (b) the ranges of years for each environment variable, and (c) the values for each environmental variable. The following example illustrates how to specify that there are two environmental variables, one of which applies to 2005 to 2008 and the other 2000 to 2005. The values for the first environmental variable are 1, 1, 2, 2 for 2005, 2006, 2007 and 2008:

```
        2                       # Number of environmental variables
        2005 2008               # range of years (series 1)
        2000 2005               # range of years (series 2)
        1 1 2 2                 # values for the environmental variable 1
        1 1 2 2 2 3             # values for the environmental variable 2
```

B.3 Time-step lengths

This input provides the duration of each time-step (the number of values entered must match the number of time-steps selected in Section A.1d). These durations need not be the same, but they must sum to 1.

```
0.1          # Length of step 1
0.7          # Length of step 2
0.2          # Length of step 3
```

B.4 Settlement specifications

There are several inputs related to "settlement".

B.4a Bounds and phase for average settlement

The values for this input are (i) the lower and upper limits for the logarithm of the average "settlement" ($\overline{R}^z$), (ii) an initial value for this parameter (which may not be used if the initial value is taken from the PIN file; see Section D.1a), and (iii) the phase in which this parameter (by sub-zone) is estimated [setting the phase for a parameter to -1 means that it is not estimated and setting to a value larger than 1 means that it is not estimated in the first phase]. One row of values must be specified for each sub-zone for which data are provided (even if the data are not used in the assessment). The following specifications (for an assessment with two sub-zones) indicate that average "settlement" should only be estimated for the first of two sub-zones (the phase is -1 for the second sub-zone):

```
        -100 100 14 1    # Virgin settlement (sub-zone 1)
        -100 100 14 -1   # Virgin settlement (sub-zone 2)
```

B.4b The range of years for which "settlement" is estimated

This range can extend beyond the assessment period (See Section A.1a) to allow the size-structure at the start of the first year of the assessment period to be estimated. This input must also specify the lower and upper bounds for the "settlement residuals" (ε_y^z) (i) and the phase in which these parameters are estimated for each sub-zone for which data were provided (not just the sub-zones which are included in the actual assessment) (ii). The initial values for the "settlement residuals" that are actually estimated are specified in the PIN file (see section D.a) or set to zero is the PIN file is to be ignored.

```
        # Settlement deviations (first and last years, limits, phase)
        1963 2011
        -5 5 2                    # Sub-zone 1
        -5 5 2                    # Sub-zone 2
```

B.4c The stock-recruitment relationship

Three lines of input values specify the stock-recruitment relationship. The first line lists the minimum and maximum, initial value (see Section D.b for how an initial value is specified using a PIN file), and phase for the steepness of the stock-recruitment relationship (i), the second line lists the lag between egg production and entering the first size-class in the model (i.e. "settlement") (ii), and the third line specifies the stock-recruitment relationship (0=none which will mean that inputs "i" and "ii" will be ignored), and 1=Beverton-Holt stock-recruitment relationship) (iii). The example below is for a case in which "settlement" is related to egg production according a Beverton-Holt stock-recruitment relationship, but steepness is pre-specified rather than being estimated.

```
        # Steepness parameters
        0.2 1.0 0.5 -3                      # Steepness parameter
        7                                   # Lag to settlement
        1                                   # Stock-recruitment relationship
```

B.4d Standard deviation of the "settlement" residuals

The standard deviation of the "settlement" residuals by year, $\sigma_{R,y}$, is defined according to the formula:

$$\sigma_{R,y}^2 = \begin{cases} \tilde{\sigma}_R^2 \, \tilde{\tau}^{y_{\text{start}}-y} & \text{if } y < y_{\text{start}} \\ \tilde{\sigma}_R^2 & \text{otherwise} \end{cases}$$

where $\tilde{\sigma}_R$ is the standard deviation of the "settlement" residuals for the assessment period, and $\tilde{\tau}$ is the rate at which σ_R changes over time for the years before year y_{start} (the taper weight). Setting the taper weight to a number less than 1 will force the model to estimate "settlement" for the years before catches are supplied to be close to mean "settlement".

```
0.5          # Settlement CV (sigma-R)
0.9          # Taper weight for SigmaR (tau)
```

B.4e Relationship between settlement deviations and environmental variables

Two inputs indicate whether the deviations about the stock-recruitment relationship are related to an environmental variable. The inputs for each area (for which data are provided) are the number of the environmental index concerned [0 if there is no relationship between the settlement deviations and an environmental variable; see Section B.2 for how environmental variables are specified] (i) and the standard deviation of the relationship between the environmental index and the "settlement" deviation (ii). If there is no relationship between the settlement deviations and an environmental variable, the value at (ii) ignored. Three are five areas in the example below, "settlement" for two of these areas is assumed to be linked to an environmental index:

```
# Link between settlement and environmental variables
  1   0   3   0   0   0
0.5 0.5 0.5 0.5 0.5 0.5
```

B.4f Timing of settlement

The input are how many times "settlement" occurs each year (i), and the time-steps during which "settlement" occurs each year, one value for each time "settlement" occurs during the year (ii). Note that when "recruitment" occurs during the year will depend on when growth is assumed to be occur and is not necessarily closely related to when "settlement" occurs. The two inputs should be "1" for an annual model.

```
2              # Number of settlement events each year
3 8            # When settlement occurs each year
```

B.4g Split of settlement to sex

The next set of inputs relates to the split of the annual "settlement" to sex and sub-zone ($\Omega_i^{s,z}$). Again, the inputs are the upper, lower and initial values for these parameters and the phases in which they is to be estimated (the initial value is set in the PIN file – see Section D.e – if a PIN file is used). One line of input must be provided for one less than product of the number of sexes and number of times "settlement" occurs during the year. Consequently, for two areas and two sexes, there would be three lines of input.

```
0 10000 1 2    # Split of settlement to sex and time-step
```

B.4h Proportion of settlement by size-class

The fraction of total "settlement" which occurs to each size-class (assumed to be the same for each time-step during which "settlement" occurs) must be specified first for males (i) and then for females (ii), for each sub-zone in turn.

```
# Fraction settlement by size-class (males then females)
# males (sub-zone 1)
0.35  0.20  0.15  0.15  0.10  0.05  0  0  0  0  0  0
# females (sub-zone 1)
0.45  0.25  0.15  0.10  0.05  0  0  0  0  0  0  0
# males (sub-zone 2)
0.35  0.20  0.15  0.15  0.10  0.05  0  0  0  0  0  0
# females (sub-zone 2)
0.45  0.25  0.15  0.10  0.05  0  0  0  0  0  0  0
```

B.5 MPA specifications

The fraction which a new MPA (see Section A.1g for where MPAs are specified) constitutes of the open area when it is first implemented is specified here. One value should be entered each MPA. As a result, if there are two MPAs in the same sub-zone and the values for this input are 0.1 and 0.1 for each MPA, it implies that the first MPA constitutes 10% of the open area and the second MPA 9% (10% of 90%). A blank line should be provided if no MPAs are to be modelled.

```
# MPA specifications (ignore if MPAs are not included in the model)
0.1  0.1               # Fraction of the remaining OPEN area in the MPA
```

B.6 Movement parameters

B.6a Between which sub-zones does movement occur

The purpose of this section is to specify between which sub-zones (which can include MPAs) movement occurs. The inputs are:

(a) the number of sub-zones which each sub-zone is connected to (note that the sub-zones for which input is specified need to include both the original (assessed) sub-zones and any MPAs; the first set of sub-zones are the original and the remaining sub-zones are the MPAs; i.e. if there are 3 assessed sub-zones and 2 MPAs; sub-zones 1−3 are the assessed (original) sub-zones and sub-zones 4 and 5 are the two MPAs); a value of "0" should mean there is no movement from sub-zone under consideration, a value of "2" that animals from this sub-zone move to two other sub-zones, etc.,
(b) whether the movement rates differ among the sexes ("1" means no and "2" yes), and
(c) the sub-zones to which movement is to occur.

The input below is interpreted as follows: (I) there are two sub-zones and each is connected to one sub-zone by movement, (II) movement is not sex-specific, and (b) sub-zone 1 is connected to sub-zone 2, (III) sub-zone 2 is connected to sub-zone 1.

```
# Movement specifications
# =====================
1 1           # Number of sub-zone to which each sub-zone is connected
1             # Sex-specific movement (estimated; set to 2 for “yes”)
2             # Destination sub-zone (sub-zone 1)
1             # Destination sub-zone (sub-zone 2)
```

B.6b Specification of movement rates

This set of inputs indicates whether the movement rates should be estimated and, the bounds on the movement rates (after logistic transformation). One line of input must be provided for each movement rate. The four values which must be supplied for each movement rate are (i) the lower and upper bounds (in logit-space), (ii) an initial value (only used if the PIN file is ignored; see Section D.g for how to specify movement rates using a PIN file), and (c) the phase in which the parameter concerned is to be estimated (setting the phase to a negative value fixes the movement rate at its initial value).

```
-100 100 -2 2   # Movement parameter estimated in phase 2
-100 100 -2 -2  # Movement parameter fixed
```

B.6c Timing of movement

How often movement occurs each year and the time-step(s) in which movement takes place is specified here (the second input must not be specified if no movement is modelled, i.e. the "timing of movement" is "0"). Note that the when during the specified time-steps movement occurs is specified at input A.2. For an annual model both inputs should be set to "1".

```
1                  # Number of movements each year
9                  # Timing of movement
```

B.7 Biological parameters

Several of the inputs in NORTH.CTL relate to the biological parameters on which the population dynamics model is based. Note that specifications for growth, weight-at-length and egg production must be provided for all sub-zones and not just those which will be assessed.

B.7a Natural mortality

Natural mortality is assumed to be independent of sub-zone, sex, size, and time.

```
# Natural mortality
# =================
0.1          # Natural mortality (M)
```

B.7b The size-transition matrices

The size-transition matrices can either be provided directly or calculated from growth parameters under the assumptions that growth is either governed by (I) a von Bertalanffy growth equation, or (II) polynomial functions (McGarvey and Feenstra, 2001). The first three growth-related inputs (needed irrespective of how growth will be modelled) are:

(i) whether growth is specified directly in the form of matrices of transition probabilities or as growth parameters (1=matrices; 2=von Bertalanffy parameters; 3=polynomial parameters),
(ii) the number of time-steps each year during which growth occurs, and
(iii) the time-steps during the year when growth occurs.

The following input would imply that there are four size-transition matrices (two for each sex) and that the size-transition matrices are specified directly rather than being calculated from parameters. Growth in this case occurs during time-steps 3 and 8.

```
# Size-transition
# ===============

1           # Is growth pre-specified or calculated from parameters
2           # Number of time growth occurs each year
3 8         # Timing of growth (end of time-step)
```

Pre-specified size-transition matrices

The next input is the size-transition matrices if "1" was entered at the "`Is growth pre-specified or calculated from parameters`" input above. If "1" is entered, the next input needs to be the number of sets of growth matrices (areas x 2). The total number of growth matrices is the number of sets multiplied by the number of times growth occurs during the year. The order of size-transition matrices should be sex (male then female), sub-zone, and time-step.

The next input is a look-up table for each combination of sex and sub-zone, including those sub-zones which are not being assessed in the current application (note that a look-up table is not provided for MPAs because the growth within an MPA is assumed to be the same as that for the sub-zone in which the MPA is located). Four values are specified for each sub-zone – sex combination (males then females) in the look-up table. The first two numbers indicate the indices for the growth matrices for the sub-zone – sex combination which are to be averaged, the next number indicates whether growth is time-blocked (i.e. growth is specified for a periods of "blocks" of years) by specifying the value for the time-block (see Section B.1), and the final number indicates whether the growth parameters are a (linear) function of some environmental covariate by specifying the index of the environmental variable (See Section B.2). It is possible to make growth for two sub-zones the same by setting the index in the first column to the index for the growth matrix which is to be used for this sex-sub-zone combination multiplied by minus one.

In the following example, the growth matrices for males in sub-zones 1 and 2 are the same while growth of females in sub-zone 1 is time-blocked and growth of females in sub-zone 2 is related to environmental variable 2. Note that growth for a sex-sub-zone combination cannot be simultaneously time-blocked and related to an environmental variable.

```
 1 0 0 0               # Growth matrices for males in sub-zone 1
 1 0 1 0               # Growth matrices for females in sub-zone 1
-1 0 0 0               # Growth matrices for males in sub-zone 2
 1 0 0 2               # Growth matrices for females in sub-zone 2
```

Growth specified as polynomial functions

If growth is to be specified in the form of polynomial functions, the next input is the maximum number of size-classes an animal can grow (e.g. “2” at this input means that an animal either stays in its current size-class or grows one size-class) and the number of parameters defining the mean and standard deviation. In the following example, the maximum number of size-classes an animal can grow through is 5, while the growth function for males in sub-zone 1 is linear in expectation (2 parameters) with a constant standard deviation (1 parameter) and that for females in sub-zone 1 is linear in expectation and standard deviation (two 2s for each type of parameter).

```
6                           # Number of jumps
2 1 2 2                     # Means and SDs (sub-zone 1)
2 2 1 1                     # Means and SDs (sub-zone 2)
```

The next input specifies the lower and upper bounds, initial values (only used if the PIN file is ignored; see Section D.i for how set initial values if a PIN file is used), and phases for each estimated parameter if growth. If growth is modelled using polynomial functions, the number of parameters can be calculated from the table above by summing the entries. For each sub-zone-time-step-sex combination, the parameters are in the order:

1) Mean constant term
2) Standard deviation constant term
3) Mean linear term
4) Mean quadratic term
5) …
6) Standard deviation linear term
7) Standard deviation quadratic term

```
# Growth parameters
 0   5   3 2                # The mean parameters
 0 0.5 0.2 2                # The constant sd
-1   1   0 3                # The linear term for the mean
```

The linear, quadratic, etc. parameters compute the mean and standard deviation of the growth increment as a function of the size class index + 0.5. These parameters are ordered by sub-zone, sex, and time-step (i.e. sub-zone 1 is first, within sub-area 1 the parameters for males are listed before those for females, and within males, the growth parameters are listed for each time-step). If growth is time-blocked or growth depends on environmental covariates, the parameters for the 2nd and subsequent time-blocks / environmental parameters are provided *after* those for the default set of growth parameters. The order is again sub-zone, sex, and time-step. Note that bounds, initial values, and phases need to be specified for all parameters within each time-step even if the intent is that not all of these parameters are to be estimated (setting the phase to a negative number can be used to avoid treating a parameter as estimable).

Growth specified as polynomial functions

If growth is to be modelled by the von Bertalanffy growth curve, the next input is the maximum number of size-classes an animal can grow (e.g. “2” at this input means that an animal either stays in its current size-class or grows one size-class). The number of parameters is 1 (for L_∞) plus twice the number of times growth occurs each year (one parameter for each of κ and σ). Note that the parameter count needs to take account of whether growth is time-blocked or related to an environmental variable. The order of the parameters is as specified above for polynomial growth functions.

```
6                                 # Number of jumps
# Growth parameters
80 300 200 4                      # An example of an Linf parameter
 0 0.5 0.1 2                      # An example of an k parameter
 0  40  10 6                      # An example of a sigma parameter
```

Measurement error

The bounds, initial value (only used if the PIN file is ignored; see Section D.j), and phase for the parameter which quantifies the rate of measurement error for the tag-recapture data (the number is the probability of an animal in size-class *j* being measured to be in size-class *j*-1 or *j*+1) should be provided here. The phase for this parameter should be negative if there are no tagging data.

```
# Alpha parameter
0.001 0.499 0.3 7                 # Specs for the alpha parameters
```

B.7c Weight-at-length

Weight-at-length can either be specified for each size-class in turn ("1") or computed from the standard weight-length relationship ("2"):

$$W_i = a(\bar{L}_i)^b$$

where W_i is the weight of an animal in size-class *i*, $\bar{L}_i$ is the mid-point of size-class *i*, and *a* and *b* are the parameters of the relationship. The first option is specified by providing the estimates of $\ell n a$ and *b*, as follows:

```
# Weight-at-length (males then females)
1
 -15.07077 3.114                               # Males (sub-zone 1)
 -15.12115 3.135                               # Females (sub-zone 1)
 -15.07077 3.114                               # Males (sub-zone 2)
 -15.12115 3.135                               # Females (sub-zone 2)
```

The second option is specified as follows:

```
# Weight-at-length (males then females)
2
19.0 21.0
```

As for growth, specifications for weight-at-length must be provided for all sub-zones for which data are provided and not just those that will be assessed.

B.7d Egg production versus size

The next biological parameter is the relationship between size and egg production. Three options are available. The first option (3) is to enter egg production-at-length for each size-class while the other options (1 and 2) are respectively:

$$Q_i = \begin{cases} 0 & \text{if } L_i < L_{\text{mat}} \\ (1+e^{-\ell n 19(\bar{L}_i - L^m_{50})/(L^m_{95}-L^m_{50})})^{-1}(\tilde{a} + \tilde{b}W_i) & \text{otherwise} \end{cases}$$

or

$$Q_i = \begin{cases} 0 & \text{if } L_i < L_{\text{mat}} \\ (1+e^{-\ell n 19(\bar{L}_i - L^m_{50})/(L^m_{95}-L^m_{50})})^{-1}\tilde{a}W_i^{\tilde{b}_i} & \text{otherwise} \end{cases}$$

where Q_i is egg production for animals in size-class *i*, L_{mat} is the lowest length-at-maturity, L^m_{50} is the size-at-50%-maturity, L^m_{95} is the size-at-95%-maturity, and $\tilde{a}$ and $\tilde{b}$ are the parameters of the relationship between weight and egg production for mature females. The “mature biomass” output from the software is “egg production” when $\tilde{a}$ and $\tilde{b}$ relate to the relationship between weight and egg production, and the biomass of mature animals when $\tilde{a}=0/\tilde{b}=1$ (option 1) or $\tilde{a}=1/\tilde{b}=1$ (option 2). When $\tilde{a}=1/\tilde{b}=0$, the “mature biomass” output is the number of mature individuals.

Options 1 and 2 are entered as follows (the first input for each sub-zone is L_{mat}, the next two inputs are L^m_{50} and L^m_{95}, and final two inputs are $\tilde{a}$ and $\tilde{b}$).

```
    # Egg production versus length
    1                      # Specified pars (1 or 2) or raw data (3)
    64  80.09 81.745 0.181 2.969       (sub-zone 1)
    64  80.09 81.745 0.181 2.969       (sub-zone 2)
```

or

```
    # Egg production versus length
    2                      # Specified pars (1 or 2) or raw data
    64   76.251   84.392     .000000181409    2.969 (sub-zone 1)
    64   80.088   94.458     .000000181409    2.969
```

Option 3 involves proving the (relative) number of eggs for each size-class

```
    # Egg production versus length
    0 0.01 0.02 …
```

B.7e Proportion of females which spawn in each time-step

One value indicating the proportion of females which spawn in each time-step must be provided here (i.e. one value for each time-step):

```
    # Proportion spawning
    0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.1
```

B.8 Selectivity and vulnerability

The exposure of an animal to harvest depends on its size and sex and this exposure can change over time owing to the impact of changes over time in vulnerability[2]. Some fleets (e.g. commercial and recreational catches) are also impacted by the Legal Minimum Length (LML), which can also change over time. The vulnerability of an animal of a given size and sex is the product of size-specific vulnerability and sex-specific vulnerability.

B.8a General vulnerability parameters

The parameters related to vulnerability must be specified for each sub-zone for which data are provided and not just for the sub-zones that will be assessed. Vulnerability is specified separately for each fleet (fishery and survey). The nine numbers which define vulnerability are:

(i) the vulnerability type (0=pre-specified; 1=logistic function of length; 2=estimate size-class-specific values; the vulnerability for a fleet can be made equal to that for another fleet by setting this input to the negative of the index for the fleet to which vulnerability should be set),
(ii) whether vulnerability is sex-specific (1=No; 2=Yes),
(iii) the number of vulnerability parameters which are to be estimated if vulnerability is estimated for a subset of the size-classes (option “3” above at input “(i)”),
(iv) whether this fleet is subject to an LML (0=No; >1=Yes),
(v) a pointer to the number of the time-blocks which determines how the LML is time-blocked (0=No time-blocks, 1+=the time-block concerned; see Section B.1),
(vi) whether vulnerability for the fleet is time-blocked (which allows vulnerability to change over time) (0=No; 1−=Yes),

---

[2] “Selectivity” in this model is not gear selectivity, but rather the combined effects of selectivity and availability – hence the term “vulnerability”

(vii) the type of high-grading function (0=no high-grading; 1=high-grading is a logistic function of length; 2=high-grading is a knife-edged function of length),
(viii) does the fleet return spawners live (1=Yes; >1 no), and
(ix) is this fleet subject to high-grading of live animals(1=Yes; >1 no).

The following example shows (I) specifications for a fleet (fleet 1) which has sex-specific logistic vulnerability and is subject to an LML, (II) a fleet (fleet 2) the vulnerability for which mimics that for fleet 1, (III) a fleet (fleet 3) which has time-blocked vulnerability, and (IV) a [survey] fleet (fleet 4) which has the same vulnerability pattern as fleet 1, is not subject to the LML and which reports (live) spawners, (live) high-graded animals, and legal animals separately.

```
# Type Sex Est Par MLS?  MLS blks Selex Blks HG Spn HG
     1   2       0    1        0          0  0   0  0   # Fleet 1
    -1   2       0    1        0          0  0   0  0   # Fleet 2
     1   2       0    1        0          1  0   0  0   # Fleet 3
    -1   2       0    0        0          0  0   1  1   # Fleet 4
```

Note that if vulnerability is to be mirrored, the row for the fleet for which vulnerability is estimated must be provided before the rows for any fleets for which mirror vulnerability for that fleet, i.e. the following input will not work because vulnerability for fleet 2 is not defined when the input for fleet 1 is being analysed.

```
# Type Sex Est Par MLS?  MLS blks Selex Blks HG Spn HG
    -2   2       0    1        0          0  0   0  0   # Fleet 1
     1   2       0    1        0          0  0   0  0   # Fleet 2
```

B.8b Vulnerability check parameter

This input is a check to ensure that the user and the program agree on how many vulnerability parameters should be estimated. Note that if high-grading is estimated (a value other than "1" in the first HG column above), the count of vulnerability parameters includes the parameters needed to define high-grading as a function of length (2 for an increasing logistic function, 1 for a knife-edged function, and 3 for a declining logistic function). A warning is output (and the program stops) if there is no agreement on the number of estimated parameters!

```
# Vulnerability parameters (used only)
16
```

B.8c Bounds, initial values and phase for estimates parameters

This set of inputs specifies the bounds, initial values (only used if the PIN file is ignored), and phases for each of the vulnerability parameters (this is only for those fleets which are included in the sub-zones included in the assessment).

```
# Fleet 1 (Sex 1; Fishery Area 1)
-5 10 1 -8
-5 10 1 -8
```

B.8d Pre-specified vulnerability

If vulnerability is pre-specified (a value of 0 in Section B.8a-i) rather than being estimated (a value of 1 or 2 in B.8a-i) for some of the fleets which are included in the assessment (fleets which are not included in the assessment can be ignored) the next input needs to list the values for vulnerability. This input should be blank if vulnerability is not pre-specified for any fleet.

```
# Vulnerability
# =-=-=-=-=-===
1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00  1.00 …
```

B.8e Legal Minimum Limits

The next set of inputs provides specifications for each LML. These scenarios are linked to fleets using the "`With MLS`" and "`MLS blocks`" options above (see Section B.8a, items "iv" and "v"). The order of the LML scenarios is the same as the order to of the fleets in the vulnerability section (with time-blocked LMLs at the end of the sequence of inputs). Thus, the input would be as follows if there are two fleets and fleet 1 has time-blocked LMLs:

```
110 105      # Default LMLs for fleet #1
110 110      # Default LMLs for fleet #2
110 110      # LMLs for fleet #1 in the second block
```

B.8f Relative vulnerability of females

This input specifies the relative vulnerability of females to males. The values input here are the lower and upper bounds, initial values (only used if the PIN file is ignored; see Section D.f for how to specify the relative vulnerability parameters using a PIN file) and phases for each parameter. There must be one relative vulnerability parameter for each time-step.

```
# Female vulnerability
0 1 0.5 -1    # Bounds, initial value, phase for time-step 1
0 1 0.5 -1    # Bounds, initial value, phase for time-step 2
```

B.9 Environmental variables related to catchability

It is necessary to specify the bounds, initial values (not used unless the PIN file is ignored; See Section D.k for how to specify initial values for these catchability parameters using a PIN file) and phases for the parameter which links catchability to environmental variables if catchability is related to an environmental variable (see Section A.7b). For example, the input here is as follows if there are two linkages, and the value of the second parameter is known:

```
# Environmental parameters
-1 1  0.1  1
-1 1  0.0 -1
```

This input should be blank if there are no environmental variables are linked to catchability.

B.10 Specifications related to fitting

These specifications relate to the weight assigned to:

(a) the fishery length-frequency data (see Section A,9),
(b) the survey length-frequency data (see Section A.9),
(c) the catch-rate data (see Section A.7),
(d) the catch-in-numbers data (see Section A.8),
(e) the tagging data related to movement (see Section A.11),
(f) the tagging data related to movement (see Section A.12), and
(g) and the puerulus data (see Section A.10)

```
# Weights and likelihoods
# =-=-=-=-=-=-=-=-=-=-=-=
0.001       # Weight (Fishery fleet Length-frequency)
0.001       # Weight (Survey fleet Length-frequency)
2.0         # Weight (CPUE data)
1.0         # Weight (catch-numbers data)
0.1         # Weight (tagging data (movement))
0.1         # Weight (tagging data (growth))
0           # Weight (Puerulus)
```

Weights can also be specified by fleet within a data type. This involves setting the following input to “1” (setting it to zero means that all fleets should be weighted equally).

```
# Detailed weights (1=Yes)
# ======================
1
```

If this input is set to “1”, the weights are entered next (no further input is required if “0” was entered). The weights are as follows for the case of 10 catch-rate series (the 2nd of which is to be downweighted by 0.5), two catch series, and three fleets for each of males and females:

```
# Now provide the weights
1 0.5 1 1 1 1 1 1 1 1                              # Cpue
1 1                                                # Numbers
1 1 1                                              # Length (male)
1 1 1                                              # Length (female)
```

B.11 Initial conditions

This section provides the inputs related to how the initial conditions are specified. The two inputs:

(a) determine how many times the iterative procedure used to calculate the vector of numbers-at-length at the start of the first year for which catches are available is applied (higher leads to more accurate results, but can slow the calculations down substantially), and

(b) the length of time over which the initial fishing mortality is averaged.

```
# Initial conditions
# =-=-=-=-=-=-=-=-=-
10              # Loop counter for initial conditions
5               # Years over which to tune
```

B.12 Concluding input

The final input is a test number. This input is used to check that the input has been correctly specified.

```
# Test Number
123456
```

The input is echoed to an output files (CHECK.OUT and SOUTH.CTL). These files should be examined to ensure that the input has been entered correctly.

C. The GENERAL file

The file GENERAL.ROC provides various control parameters.

(a) Whether parameter estimation should occur (values of 1+) or whether the model should simply be projected forward using the values in the PIN file (or the values specified at the initial parameters fields if the PIN file is ignored) (value of −1 and less). Setting this parameter to “−1” is useful when checking that the input files are correctly specified.

```
#1           # estimate or project
```

(b) the level of diagnostics to be produced. Values of 1 and 2 are normal, but higher values (which can produce enormous amounts of output) should be selected if problems are to be diagnosed

```
2             # 1 basic diagns; 2 additional diags; 3 ??
```

(c) specifications for MCMC sampling. These two inputs are currently ignored.

```
1000         # Burn-in form MCMC
1            # Thinning rate for MCMC
```

(d) The next input should be set to 1 to check that the model is correctly calculating the initial state. It should not be changed by the user.

```
-1           # Check the initial state
```

(e) The next input in this file allows the user to ignore the PIN file (value=1) and base estimation on the values specified in the CTL file. This option should be selected if many runs are done and the user wishes to ensure that she/he can replicate the results.

```
0            # Set this to "1" to ignore the PIN file
```

(f) The next input in this file is a flag which indicates that a control rule should be applied. It was created for a different project and the value associated with this parameter should generally be set to 0.

```
0            # Number of projection years
```

(g) The next three input specify the current TAC, the minimum TAC and the maximum TAC. These inputs are only used if the number of projection years is non-zero.

```
250000                  # last TAC
100000                  # Minimum TAC
500000                  # Maximum TAC
```

(h) The next five inputs in this file are (i) the year which is specified to the reference year for the projections, (ii) the year a recovery plan started, (ii) the year a rebuilding plan started, (iv) the amount by which the TACC can be reduced, and (v) the amount by which the TACC can be increased. These inputs are only used if the number of projection years is non-zero.

```
1951                    # Reference year
2010                    # Start of recovery plan
2010                    # Start of rebuilding plan
0.5                     # Amount by which TACC can be reduced
1.1                     # Amount by which TACC can be increased
```

D. The PIN file

The file ROCK23A.PIN file contains the initial values for the parameters of the model (used if the PIN file is not ignored; see Section C.e). The performance of the non-linear minimization method used to estimate the values for the parameters depends critically on how close the initial values are to the best estimates for the model parameters. AD Model Builder reads the PIN file ignoring any comment lines (lines which start with "#"). Therefore, the program may actually run (but not give sensible results) even if the wrong number of initial values is provided. The PIN file can be checked by setting the value for input "e" in "GENERAL.ROC" file to "-1" and examining the file ROCK23A.PAR. It should match ROCK23A.PIN. The file CHECK.OUT also lists the number of parameters of each type which need to be specified.

The general structure of the PIN file is as follows (the specifications are provided for an assessment with two sub-zones and 20 "settlement" residuals – the number of "settlement" residuals is calculated by the program; the PAR file should be checked to ensure that the correct number of "settlement" residuals are specified).

(a) The parameter values relate to the logarithms of the average "settlement"s, $\bar{R}_0^z$ (see Section B.4a); for the case in which there are two sub-zones:

```
# log_R0
10 12
```

(b) The steepness of the stock-recruitment relationship (see Section B.4c):

```
# Steepness
1.000
```

(c) The vulnerability parameters (see Section B.8c). Number of vulnerability parameters depends on how vulnerability is specified. For the case in which there are there are two commercial vulnerability blocks, the number of parameters is 4 (2 parameters of the logistic curve x 2 blocks); note that the parameters are in log-space

```
# SelPars
4 3
4 3
```

Note that parameter values need to be provided (and the number depends on the options specified when defining vulnerability) that even if vulnerability is not estimated (phase <1).

(d) The parameters related to the "settlement" residuals (see Section B.4b). One initial value needs to be provided for each "settlement" residual

```
# Eps (one value for each 1965, 1996, etc.)
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
```

(e) The parameters related to the split of the annual “settlement” between sexes and “settlement” events (see Section B.4g). Therefore, three values need to be provided if “settlement” occurs twice a year and there are two sexes (there are actually four parameters, but the fourth is simply the difference between the first three and unity):

```
# PrSxSn0
1 1 1
```

(f) The relative vulnerability of females to males for each time-step (see Section B.8f); one initial value should be provided for each time-step. These parameters need to be provided even if the relative vulnerability is not estimated.

```
# VulnEst
1 1 1 1 1 1 1
```

(g) The movement rates (see Section B.6b). The number of values should be equal to the number of movement parameters (twice this if movement is sex-specific). However, a single value must be provided even if movement is not estimated. There will be a total of four movement parameters (sub-zone 1 to sub-zone 2 for males (i); sub-zone 2 to sub-zone 1 for males (ii), sub-zone 1 to sub-zone 2 for females (iii); sub-zone 1 to sub-zone 2 for females (iv)) if there are two sub-zones and movement is sex-specific (note that the parameters are in logit space).

```
# EstMovePars
0.10.1 (males)
0.20.1 (females)
```

(h) The parameters related to the catchability for FIMS surveys relative to catch-rate series (see Section A.7c). One parameter is needed for each of the FIMS series (which one less than the number of CPUE Types – see Section A.7).

```
# qF
0.3
```

(i) The parameters related to growth. The number of growth parameters depends on for how many sub-zones are growth is to be estimated (rather than being pre-specified or mimicked), the number of time-blocks and whether growth relates to an environmental variable (see Section B.7b). The following example shows how von Bertalanffy growth parameters (i.e. option “2” in Section B.7b) would be specified if (i) there are two growth events each year (so the growth matrix for each year depends on five parameters), (ii) there are two areas, (iii) growth for males in sub-zone 2 mimics that in sub-zone 1, (iv) growth for males in sub-zone 1 is time-blocked (by a blocking structure with 2 blocks), and (v) growth for females in sub-zone 1 is related to an environmental variable.

```
# Growth parameters
200 0.1 10 0.1 10    # Males in sub-area 1 (reference values)
150 0.1 10 0.1 10    # Females in sub-area 1 (reference values)
150 0.1 10 0.1 10    # Females in sub-area 2 (reference values)
200 01 10 0.1 10     # Block 1 values for males in sub-area 1
200 01 10 0.1 10     # Block 2 values for males in sub-area 1
0 0 0 0 0            # Environmental links for females in sub-zone 2
```

The initial values are set so that time-varying growth is not present (although it could be estimated to be once the program is complete; whether parameters are changed from their initial values depends in the phases set when setting the bounds for the vulnerability parameters). Note also that as the growth parameters are linked to the environmental covariates by an exponential transform, “0” corresponds to no effect of an environmental covariate on the parameter.

If the growth matrices are pre-specified (option “1” in Section B.7b) then a single input parameter is needed.

```
# Growth parameters
1
```

(j) The probability of incorrectly measuring an animal when it is recaptured (see Section B.7b).

```
# Alpha:
0.248432
```

(k) The parameters related to the parameters which link catchability to environmental indices (see Section B.9). One value should be provided even if the parameter concerned in not estimated (phase < 1). The example input below would be entered if three environmental variables were linked to catchability.

```
# Q pars
0 0 0
```

The final entry in the PIN file must be:

```
# Dummy
  0
```

E. Outputs

The main output files are ROCK22D.REP and DIAGFILE. The files CHECK.OUT, SOUTH.DAT and SOUTH.CTL echo the input and should be checked to ensure that the data have been entered correctly. A file AEPOUTPUT.OUT is created if the projection options are used.

E.1 ROCK23A.REP

The file ROCK23A.REP lists the detailed population dynamic outputs:

(1) The harvest rates by year, time-step and sub-zone (note that the output starts at the start of burn-in period)
(2) The exploitable biomass by year, time-step and sub-zone (note that the output starts at the start of burn-in period)
(3) The time trajectory of egg production by sub-zone (separate sub-zones in each column).
(4) The time trajectory of "settlement" by sub-zone (separate sub-zones in each column).
(5) The fits to catch-rate data.
(6) The fits to the catch-in-numbers data.
(7) The fits to the length-frequency data.
(8) The fits to the larval data
(9) The midpoints of each size-class, weight-at-length, maturity-at-length, egg production-at-length.
(10) Vulnerability, relative female vulnerability, the size-breakdown of the "settlement".
(11) The size-transition matrices
(12) The numbers-at-length by year, time-step and sub-zone
(13) The vulnerability (total, landed and discarded), and relative probability of high-grading.

E.2 DIAGFILE

The file DIAGFILE summarizes the fits to the data further. The data in this file are less formatted that those in ROCKX.REP to make graphical summarises of the data easier to construct. The specific information provided in DIAGFILE is:

(1) The fits to catch-rate data.
(2) The fits to the catch-in-numbers data
(3) The fits to tagging data (note that the fit to the tagging data is aggregated by numbers released and recaptured by sub-zone and time of release/recapture).
(4) The fits to the length-frequency data.

References

McGarvey, R. and J.E. Feenstra. 2001. Estimating length-transition probabilities as polynomial functions of premoult length. *Marine and Freshwater Research* **52**, 1517−1526.

Appendix: Glossary of terms

FIMS: Fisheries Independent Monitoring Survey

Fishery Fleet: A fleet for which the removals are sufficiently large that they should be taken into account; fishery fleets reflect commercial, recreational or illegal removals.

Fleets. Fleets are either fisheries or surveys. The key difference between fishery and survey fleets are that the catch by a fishery fleet is removed from the population while that by a survey fleet is not. Fleets are associated with a sub-zone[3] (although there is an exception to this for size-composition information). There may be (usually will be) several fleets in each sub-zone.

MPA: Marine Protected Area.

Phase: The phase assigned to a parameter indicates when (and if) it should be estimated. A parameter with a phase of −1 (or less) is not estimated but set to its initial value. A parameter with a phase of 1 is estimated in the first round of minimizations (and in all subsequent rounds) whereas a parameter with a phase of 2 is estimated in the second and all subsequent rounds of minimizations.

Recruitment: The number of animals growing to be larger than minimum legal size (i.e. becoming available to fishery).

Settlement: The number of animals entering the model.

Sub-zone: Sub-zones are areas within the model; each “sub-zone” is associated with a local population.

Survey fleet: A fleet for which the removals are negligible.

Time-step: 1 for an annual model or 2+ for a monthly or weekly model.

Vulnerability: The combined impact of gear selectivity (the relative probability among size-classes of being captured) and of availability (the relative probability among size-classes of being located to be the fishery).

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[3] The terms “sub-zone” and “area” are used interchangeably in this document.

Environmental effects on lobster and crab fisheries of the world

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Abstract

Crabs and lobsters are grouped in the decapod suborder of Reptantia, which is no longer widely used in crustacean systematics but does describe a group of animals with broadly similar life history and of significant commercial value. The fisheries for these species are shaped by environmental variation through the distribution ecology, productivity or even their market traits such as colour and size. Many crabs and lobsters have a wide latitudinal distribution and therefore are exposed to significant abiotic gradients throughout their geographic range. Environmental factors affect reptantians throughout their complex life cycle, including timing and length of the spawning period, the duration and quality of the larval stages, the level and spatial distribution of the settlement, growth rates and size of the juveniles, size at maturity, and catchability. The most consistent environmental response is of growth and reproduction to temperature. Growth rates increases with increasing temperatures in a parabolic function, tapering and then declining as the boundaries of thermal tolerance are reached. With increasing temperature the intermoult duration decreases. Once the upper thermal boundary is reached, increases in temperature result in longer intermoult duration and smaller increments so that growth is reduced. Declines in temperature generally suppress moulting, and consequently reptantians rarely moult in winter. Increasing temperature decreases the time for egg incubation, larval development and the maturational age. Catchability increases with water temperature and also varies, although less predictably, with moon phase and wind strength. Catchability decreases with an increase in population density. Larval settlement of many

reptantian species depends on current strength, increasing with the strength of certain local currents. This pattern may be due to the physical movement of water bodies and their advective effects or the co-varying changes in primary production or temperature. Similarly, when wind has had an effect on catchability or recruitment it is likely to be due to co-varying factors such as temperature. Reptantians can tolerate a wide-variety of conditions and have flexible life-histories to respond to conditions throughout their broad geographic ranges. As temperature and ocean pH change with climate change there are a number of potential risks to fisheries for these crustaceans. Hatching too early or late, as a result of shifting temperature regimes could result in decapod larvae missing the primary peak of zooplankton blooms. This mismatch in timing would affect the size and quality of settlement pulses. There is some evidence of longer and later spawning season in larger females which is hypothesized to be a response to increase the concurrence of larvae with plankton blooms. As higher temperature increases, increased catch-rates due to increased activity may be another side-effect of climate change. Information on environmental effects on reptantians not only assists in understanding probable effects of climate change but also seasonal and interannual changes in fisheries production.

Introduction

Lobsters and crabs support valuable fisheries from the poles to the equator. Annual harvests in 2010 were 1,424,867 tons of crabs and 279,685 tons of clawed and spiny lobsters, which has been steadily increasing since 2004, representing an annual revenue of US$6,209 million from worldwide fisheries (FAO 2010).

A range of environmental factors affect both lobsters and crabs throughout their complex life cycle. The distribution and abundance of the pelagic larvae is mainly determined by abiotic factors (e.g. currents, wind, and temperature), whereas the benthic adult stage is governed by biotic factors (predation, food availability, competition) (Cobb and Wahle 1994). Phenotypic traits that vary in response to environmental change are essentially recruitment strategies designed to adapt to variable external conditions, encompassing trade-offs in age at reproduction and longevity, fecundity, degree of parental care, larval duration and post-settlement mortality (reviewed by Cobb et al. 1997).

Table 1. Key commercial decapod species reviewed and their geographic range

Family	Species	Common name	location
Nephropidae Clawed lobster	*Homarus americanus*	American lobster	East coast of North America
	Homarus gammarus	European lobster	Eastern Atlantic Ocean, Mediterranean Sea and parts of the Black Sea
Palinuridae Spiny lobsters	*Panulirus argus*	Caribbean spiny lobster	Western Atlantic ocean
	Panulirus cygnus	Western rock lobster	West coast of Australia
	Jasus edwardsii	Southern rock lobster	East Coast of southern Australia
Lithodidae	*Paralithodes camtschaticus,*	Red king crab	Bering Sea
Cancridae	*Cancer magister*	Dungeness crab	West coast North America
	Cancer pagurus	Edible crab, brown crab	North sea, North Atlantic ocean, Mediterranean Sea
Portunidae	*Portunus trituberculatus*	Japanese blue crab	Coast of East Asia
	Portunus pelagicus	Blue swimmer crab	Africa, Southeast Asia, East Asia, Australia and New Zealand.
	Callinectes sapidus	Atlantic blue crab	western Atlantic Ocean, the Pacific coast of Central America, and Gulf of Mexico.
	Scylla serrata	Mud crab	Africa, Australia and Asia
Orgeoniidae	*Chionoecetes opilio*	Snow crab	northwest Atlantic Ocean and north Pacific Ocean

Recruitment variability is assumed to be higher in spiny lobsters (Palinurids) and *Cancer* crabs than in clawed lobsters, as they typically have higher fecundity (1 to 4 orders of magnitude higher), smaller eggs, longer larval duration and therefore presumably lower larval survival (Cobb et al. 1997). Large number of poorly provisioned propagules, combined with variable survival and transport, have the potential for producing considerable variation in recruitment (Incze et al. 1997). Spatial and temporal variations in life history parameters are largely attributed to environmental heterogeneity. Identifying any long-term trends associated with the key environmental factors shaping the fisheries may aid in predictions of future biomass (Winemiller and Rose 1992). From a fisheries management perspective, changes in growth rate, natural mortality and catchability are three critical factors that can be included in the stock assessments to manage species. From a biological perspective however all species have specific tolerance limits for temperature and other environmental variables, which limit their geographic distribution.

Few attempts have been made to describe general patterns across species of how environmental variation and climate change will affect decapods crustaceans. The effects of environmental variables on larval recruitment of American lobster were reviewed by Aiken and Waddy (1986), and the effects of temperature on crustacean growth were reviewed by Hartnoll (1982). This review will focus on the influence of environmental variables on lobster and crabs species with information mainly from the commercial species that have received most research attention (Table 1).

Growth

A major determinant of the influence of environmental variation on reptantian crustaceans is their mode of growth. Crustaceans have a largely inextensible exoskeleton that is replaced intermittently in stepwise moults (or ecdysis) resulting in a discontinuous growth (Hartnoll 1982). At each moult the old exoskeleton is shed, allowing the animal to expand before new exoskeleton hardens. This increase in size is termed the moult increment, while the intermoult period is the duration between two successive moults. Growth rate in crustaceans is thus a function of both moult increment and moult frequency and these two factors respond differently to environmental variation (Hartnoll 1982).

Temperature and growth

Temperature is a major factor influencing the physiological and ecological properties of marine species (Kinne 1970; Aiken and Waddy 1986). Temperature varies on both temporal (e.g., daily, seasonal) and spatial (depth and latitude) scales in aquatic systems although variation is generally less than in terrestrial ecosystems because of thermal buffering of water. Temperature influences the rate of metabolism and growth, and reproduction in poikilotherms such as crabs and lobsters, and has a major influence on development in early life history stages (Leffler 1972; Le Moullac and Haffner 2000; Tlusty et al. 2008a). Variation in water temperature may alter absolute growth, food availability, timing of moulting, mating, spawning and recruitment, and the amount of growth, all of which can have cascading effects on population dynamics. Many crab and lobster species have a wide latitudinal distribution (Table 1) and are therefore exposed to significant temperatures throughout their geographic range. As with all living organisms, their geographical range is primarily governed by both an upper and a lower thermal limit (Rombough 1997), as well as the availability of contiguous habitat.

Growth rate is generally positively correlated to temperature amongst crustaceans within the thermal tolerance of each species (Hartnoll 2001b). Elevated (warm) temperature can accelerate growth by shortening the intermoult period, or increasing the moult increment, or both. There is an optimum temperature effect within the thermal tolerance of a species, whereby growth increases with increasing temperature to a maximum, before declining near the upper thermal limits as higher temperatures have negative effects (Hartnoll 1982). Above the thermal optimum both the intermoult period and the moult increment are negatively affected by temperature. The temperature range at which growth is optimal is specific to species but also varies within a given population.

Temperature can affect growth in different ways before and after the onset of maturity. Faster juvenile growth in response to warmer water can be offset by reduced growth rates at maturity resulting in a smaller asymptotic maximum and lower stock productivity. For example, size at maturity of *Panulirus cygnus* is smaller in the northern sites of the fishery, which appears to be linked to higher water temperatures although is confounded by high density in this region (Melville-Smith and De Lestang 2006). In laboratory experiments, the weight gain of post-pueruli western rock lobster (*Panulirus cygnus*) almost doubled at 23 °C compared to ambient temperature (between 15.6°C –23.1°C) (Johnston et al. 2008). Year 1 juveniles showed a 50% increases in weight at the higher temperature treatment whereas little difference was observed for year 2 juveniles (weight gain at 23 °C versus ambient: 23% versus 21%) (Johnston et al. 2008).

Temperature and moulting

Metabolic processes in poikilotherms increase at higher temperatures including the mobilization of reserves and the preparatory stages needed for moulting (Hartnoll 2001b). For example, moulting of adult *Homarus americanus* occurred two weeks earlier when temperatures were higher in 1994 (18.3–20 °C in July to September) compared to 1993 (15.1–17 °C in the same period) (Aiken 1973). The effect of temperature on intermoult period varies immensely between species and also between individuals of the same species. As a result, the timing of moulting for individuals of *Panulirus cygnus* from the same site can vary by several weeks (Caputi et al. 2009).

When measured within the species thermal tolerances increasing temperature almost universally decreases the intermoult period in larvae, juveniles and adult lobsters and crabs. Lobster examples include *Jasus edwardsii* phyllosoma (Bermudes and Ritar 2008), *Panulirus cygnus* (Liddy et al. 2004), *Panulirus argus* (Lellis and Russell 1990), *Panulirus homarus rubellus* (Kemp and Britz 2008), *Jasus verreauxi* (Moss et al. 2001), *Homarus americanus* larvae (Templeman 1935), *Panulirus japonicus* (Matsuda and Yamakawa 1997), *Panulirus interruptus* (Serfling and Ford 1975), and crab examples include *Paralithodes camtschaticus* (Stoner et al. 2010), *Pseudocarcinus gigas* (Gardner et al. 2004), *Carcinus maenas, Callinectes sapidus,* (Leffler 1972; Fisher 1999), *Hyas araneus* (Anger 1983), *Cancer irroratus* (Johns 1981), *Ranina ranina* (Minagawa 1990), *Lithodes aequispinus* (Paul and Paul 1999), and *Cancer magister* (Kondzela and Shirley 1993).

When the effects of temperature on the intermoult were examined at the upper boundary of the species thermal range then the response to temperature was not consistent. A temperature increase towards the upper limit increased the intermoult period and mortality in *Jasus edwardsii* phyllosoma (Thomas et al. 2000; Bermudes and Ritar 2008), *P. argus* (Lellis and Russell 1990) and *Cancer magister* (Kondzela and Shirley 1993). However the opposite was seen in *P. cygnus* and *P. argus* phyllosomsa and *C. magister* adults where higher temperature reduced moult increment (Lellis and Russell 1990; Kondzela and Shirley 1993; Liddy et al. 2004). These contrasting observations may be caused by differences in the nature of metabolic processes which begin to decrease above the upper thermal limit in poikilotherms due to energetic imbalance (e.g. reduced feed intake versus raised nitrogen excretion (Bermudes and Ritar 2004).

Growth is reduced at lower temperatures to the point where moulting is completely suppressed. For example, *Homarus americanus* and *Callinectes sapidus* do not moult from November to April (Hartnoll 1982; Ju et al. 2001) and *C. magister* did not moult when temperature was 0 °C (Kondzela and Shirley 1993).

Frequency of moulting and the moult increment are influenced differently by changes in temperature which complicates interpretation of the effect of temperature on growth. Hartnoll (1982) reviewed four crustaceans where increasing temperature had no effect on moult increment, eight that displayed a reduced increment with raised temperature, and only two showed an increase in moult increment with increased temperature. A decrease in temperature results in a delay of larval development in the spider crab *Hyas araneus* which is stronger than the acceleration caused by an equally great increase (Anger 1983). In *Cancer magister* the effect of temperature on growth was mainly through change in the intermoult duration (Kondzela and Shirley 1993). In species and life stage where moulting is annual such as *J. edwardsii*, the intermoult period is less flexible so the effect of temperature on growth is mainly through the size of the moult increment (Gardner and Van Putten 2008). Moult increment in the Artic lyre crab *Hyas coarctatus* was observed to initially increase between 6 °C and 9 °C before decreasing between 9 °C and 18 °C (Anger 1984). Maximum growth increment of captive inbred Stage I *Jasus edwardsii* phyllosoma occurred at a mid-range temperature 18.2 °C compared, to the higher and lower temperatures (Bermudes and Ritar 2008). Increased temperature had an opposing effect on growth in *Carcinus maenus* by shortening the intermoult duration, but reducing the moult increment (Mohamedeen 1990). However, the general pattern appears to be that the effect of temperature on intermoult duration is more influential on growth than change in moult increment (Hartnoll 2001a).

Reproduction and Ontogeny

Temperature and timing of reproduction

Timing of reproduction within a season

The timing of reproduction is critical to survival of a species. Firstly, individuals must time their spawning to coincide with reproductive ripeness in a mate, and secondly they must time it so their offspring have the best possible chance of survival. The timing of reproduction of most crustaceans relies on both photoperiod and temperature to ensure that spawning is synchronized (Lawrence and Soame 2004). Timing larval release to match with abundance of food maximizes the chances of survival of the most number of larvae (match-mismatch hypothesis, Cushing 1972). Increasing sea temperatures may accelerate growth at first and increase recruitment to the fishery (if daily egg loss is constant, shorter incubation will result in more eggs hatching Oviatt (2004)). Concurrently, an increase in temperature may increase the period over which lobsters and crabs release their larvae (Tlusty et al. 2008b). Timing of reproduction within a season and larval duration are inextricably linked. Different temperature conditions at the time of egg extrusion alter the length of the embryonic development, ranging from one year in multiparous females to two years in primiparous female snow crabs, (*Chionoecetes opilio*) (Moriyasu and Lanteigne 1998; Webb et al. 2007). At temperatures below 1 °C the one-year reproductive cycle is replaced by a two-year cycle (Webb et al. 2006). *C. opilio* is a cold water stenotherm, i.e, it can only survive a very narrow range of temperatures (Moriyasu and Lanteigne 1998; Kuhn and Choi 2011), with a reproductive cycle that is temperature dependent. Primiparous females (bearing their first clutch) mate in February/March (Moriyasu 1987), and multiparous females (bearing their second or ulterior clutch) mate in April/June (Moriyasu 1987).

Timing of first reproduction

Temperature stimulates early ovarian development (Annala et al. 1980), and so reproductive maturity is accelerated at higher temperatures. The size at onset of sexual maturity depends on other factors besides temperature, such as metabolic rates, population density, food availability and other environmental and/or genetic variables (Annala et al. 1980). Life-time fecundity is a function of clutch size and number of broods (Table 2). With the onset of sexual maturity, organisms face a trade-off between the amounts of energy used for reproduction and growth (Stearns 1976; Partridge and Sibly 1991; Zera and Harshman 2001). Consequently those starting reproduction earlier will have less energy available for growth than those that reproduce later. Female *Homarus americanus* mature between 55 mm and 110 mm carapace length (CL), aged generally 5–9 years (Waddy and Aiken 1992; Fogarty 1993). Warm-water spiny lobsters are younger (2–4 years) and smaller (40–75 mm CL) at maturity than cool-water species (5–7 years and 55–110 mm CL) (MacDiarmid 1989; Gardner et al. 2006; Frisch 2007). Likewise, Cancer crab females in warm waters mature earlier and at smaller sizes than those in cool waters. There is wide variation in size at first reproduction (10–130 mm carapace width (CW)), but less in age (1–3 years) at first reproduction (Shields 1991). In the American lobster, *Homarus americanus,* the consequence of temperature increases within their thermal tolerance on growth is that the time to reach a particular stage of the life cycle (e.g. the end of larval development, or the onset of sexual maturity) is decreased, but the size on attaining that stage is also decreased. In simpler terms, the life span is shortened and the body size is decreased (Wahle and Steneck 1991). This pattern does not hold across all species though. The size at which female southern rock lobster mature in Tasmania follows a latitudinal decline from warmer water in the North to colder waters in the South (Gardner et al. 2006). However as the latitudinal trend in the same species is the opposite in New Zealand, additional factors to temperature must be involved.

Frequency of reproduction

Lobsters and crabs exhibit a variety of maturity schedules depending mainly on water temperature and latitude. Clawed lobsters spawn every one or two years, spiny lobsters spawn once (temperate species) or several (tropical species) times per year, and most Cancer crabs spawn only once per year (Cobb et al. 1997). At the northern end of its distribution, *Homarus americanus* have two different spawning strategies, similar to that of the snow crab (Webb et al. 2007). Larger females, most likely multiparous, with a 2-year reproductive cycle, generally spawn earlier in the season. Smaller females, most likely primiparous, with a 1-year cycle generally spawn later (Gendron and Ouellet 2009). This results in different trajectories of egg development, and as a consequence larvae from ES/multiparous and LS/primiparous encounter different environmental conditions at hatching and during subsequent larval development. These two reproductive strategies which spread larval production over time are an adaptation to environmental uncertainty (Gendron and Ouellet 2009). The crab, *Cancer setosus,* produces more egg masses per year at higher temperatures. At temperatures similar to those found at the centre of its' range they can produce three egg masses per year, and only one egg mass per year at temperatures similar to those at the northern and southern extent of their range (Fischer and Thatje 2008).

Table 2. Relative fecundity of key fisheries species

Species	Fecundity	Reference
Homarus americanus	300–100,000: 17,000–220,000	(Estrella and Cadrin 1995), (Herrick 1896)
Homarus gammarus	100,000–1,000,000	(Cobb et al. 1997).
Jasus edwardsii	38,000–540,000 43,900–660000	(Annala and Bycroft 1987), (Linnane et al. 2008; Green et al. 2009)
Most of the Cancer crabs	Up to 3,000,000	(Cobb et al. 1997).
Panulirus cygnus *Panulirus argus*	116,000–682,000 160,000–1,600,000	(Chubb 2000) (Cruz & de León 1991; Fonseca-Larios et al 1998)

Eggs and Embryos

Temperature is the major factor that controls embryonic development duration (time from fertilisation to larval hatching) as well as the larval development duration (time from larval hatching to metamorphosis with recruitment to the benthos) in lobsters and crabs. Embryonic development occurs once the eggs have been extruded and fertilised and attached to the pleopods on the external surface of the underside of the female's abdomen. In crabs and lobsters, the egg incubation period decreases with increasing temperature following a similar trajectory between sepcies, according to the equation:

$$y = 0.5906x^2 – 29.725x + 429.09, R^2 = 0.8619 \text{ (Figure 1)}.$$

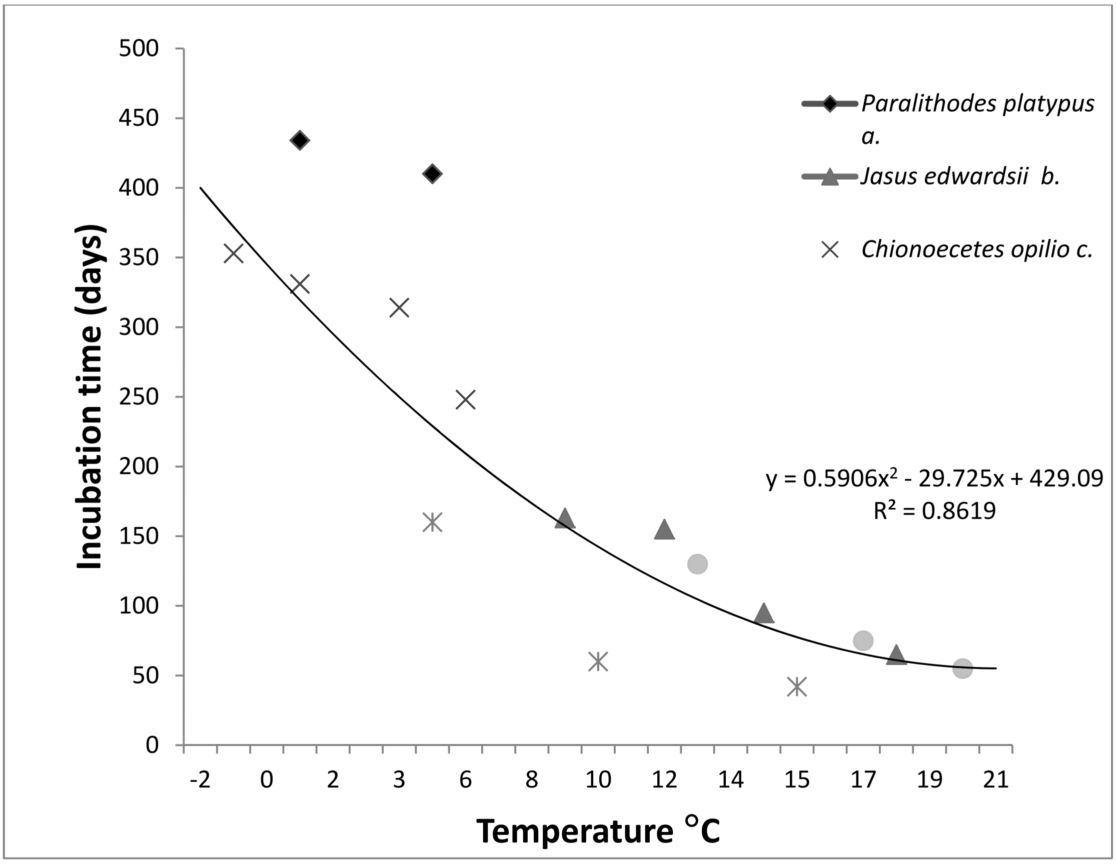

Figure 1. Egg incubation temperature and the resultant incubation time for select commercial crustaceans. a. (Stevens et al. 2008), b. (Tong et al. 2000), c. (Webb et al. 2006), d. (Shirley et al. 1987), e. (Hamasaki 2003), f. (Moss et al. 2004).

Incubation time in the sub-arctic blue king crabs (sub-arctic) *Paralithodes platypus* ranged from 410 days at 6.1 °C to 434 days at 2.3 °C and increased with decreasing temperature (Stevens et al. 2008, Fig. 1). In the temperate *Cancer magister* while developmental rate increased with decreasing temperature to a point, all adults and eggs died before hatching occurred at 1 °C (Shirley et al. 1987). In the mud crab *Scylla serrata* egg incubation period decreased exponentially from 30 to 10 days with increasing mean temperature in the range 20.3–30.0 °C (Hamasaki 2003). Time from fertilization to hatch was positively correlated to temperature in *Maja brachydactyla* (Martin and Planque 2006). American lobster eggs will go into diapause if the temperature drops below 5 °C (Perkins 1971), and eggs will be brought out of a developmental stasis only when temperatures peak over 10 °C (Helluy and Beltz 1991). Given the shape of the temperature/egg incubation curve (Figure 1), it is crucial to consider the full thermal spectrum and not just maximal summertime temperature when evaluating the impact of ocean global warming on crustaceans.

Salinity on Eggs and embryos

Oceanic ecosystems have a relatively stable salinity around 35 ppt (except the Red and Baltic Seas, which have distinct haloclines), but they fluctuate both seasonally due to rainfall or aseasonally due to oceanic upwelling or downwelling, and vary close to the coast due to the effects of freshwater inflow. Salinity has a profound effect on water density and therefore circulation and stratification, especially in estuaries (Johnson et al. 1991). Numerous chemical reactions follow changes in salinity as most equilibrium and rate constants are salinity dependent. For instance, an increase in salinity results in pH increase, whereas it gives rise to a decline in organic matter solubility (Cai et al. 1998).

Many species of crustacean inhabit coastal and estuarine areas where salinity fluctuates due to rainfall and freshwater in-flow. Lobsters and crabs are generally restricted by a lower salinity threshold value (Gibson and Najjar 2000). In many species, adult and larval crustacean can avoid low salinity by modifying their behaviour

(Charmantier et al. 2001). Species such as *Hemigrapsus edwardsii* and *Hemigrapsus crenulatus* are euryhaline crabs (that is, capable of tolerating a wide range of salinities) inhabiting mainly tidal and estuarine areas and therefore can survive with a salinity range of 3-45 psu (Taylor and Seneviratna 2005).

Embryo and some stages of larval development occur prior to the differentiation of branchial and excretory organs for adult osmoregulation, but curiously there is salinity tolerance in these stages also (Taylor and Seneviratna 2005). The responses of different life stages to changes in salinity are somewhat contradictory. On the one hand, a fairly recent review of adaptation to salinity throughout the life cycle of Homarids, (Charmantier et al. 2001) suggest that embryos are osmoconformers[1] and are osmotically protected by the egg membrane. On the other hand, Aiken and Waddy suggest that embryonic development of *Homarus americanus* is affected by salinity as embryos have higher osmotic pressure and take longer to adapt to low salinities than larvae (Aiken and Waddy 1986). It appears that crustacean embryos employ a range of strategies to survive in a variable salinity environment, and can osmoconform or osmoregulate[2] . There are a number of reviews which detail the ontogeny of osmoregulation and salinity tolerance in crustaceans, and we recommend these for further details (Charmantier 1998) (Charmantier et al. 2001).

Oxygen on Eggs/embryos

In addition to salinity and temperature, the amounts of dissolved gases (mostly oxygen and carbon dioxide) are the most important components of sea water that influence life forms. Dissolved oxygen is required for respiration, and in adult marine animals is extracted from water flowing over gill filaments. In temperate water, oxygen levels range from 0 to over 20 ppm. The amount of oxygen in seawater declines with increasing temperature and increases with declining salinity (Weiss 1970). Some species can survive in areas that have regular oxygen fluctuations, e.g., the Norwegian lobster, *Nephrops norwegicus* (Baden et al. 1990).

In the early life stages of crustaceans there are different pathways for adjusting to the local oxygen environmental compared with adults. Early life stages may use a range of relatively passive options to counter a fluctuating oxygen environment and regulate oxygen uptake, by adjusting cardiovascular parameters like heart rate, stroke volume, haemolymph flow, ventilation and changes in O_2-binding properties of respiratory pigments (McMahon 2001). The eggs of *Carcinus maenas* and *Cancer pagurus* show some oxyregulatory ability which disappears after hatching (Wheatly 1981; Naylor et al. 1999). In most crustacean species, females brood their eggs on the underside of their abdomen, and therefore can actively control the oxygen environment of the offspring. Maternal fanning and mobility can buffer eggs from environmental fluctuations in oxygen. Female *Cancer pagurus* can detect oxygen levels and adjust their ventilation behaviour accordingly (Naylor et al. 1999). Egg mass oxygen demands in *C. pagurus* , *C. setotus* and *N. norwegicus* increase with ontogeny and active egg mass ventilation increased accordingly (Naylor et al. 1999; Baeza and Fernandez 2002; Eriksson 2006), in patterns similar to those in brooding fish (Green and McCormick 2005). Embryos of two brachyuran crabs *Cancer setosus* and *Homalaspis plana* on the centre of an egg mass have lower oxygen consumption and slower development than embryos at the periphery, causing an asynchrony in development (Fernández et al. 2003). Adult Norway lobster, *Nephrops norvegicus,* inhabit areas where oxygen deficiency (<30% oxygen saturation) frequently occurs during autumn the bottom waters (Baden et al. 1990). In a laboratory examination of female behaviour and embryo response to a range of oxygen conditions, females increased the venitaltion of their eggs in normoxic (> 90% oxygen saturation) and hypoxic condition (30% oxygen saturation) (Eriksson 2006) (Eriksson 2006) (Eriksson 2006) (Eriksson 2006) (Eriksson 2006) .While early and late embryos survived acute exposure to 5–95% oxygen saturation, a side-effect was that late embryos displayed premature hatching (<16% oxygen saturation) and decreased survival rate (<7% oxygen saturation) (Eriksson 2006).

Given the range of life stages in a many crustacean, they must have evolved to be able to adapt to the environmental conditions presented at each life stage. In the eggs where the two means to escape unfavourable condition are maternal behaviour or physiological adaptation, it is therefore not surprising that they are more tolerant to hypoxia than some later life stages as they often have little choice to avoid it (Eriksson 2006).

Hatching and early development

Temperature on hatching and early development

Many temperature thresholds or relationships with development rate are determined in tank experiments and aquaculture, where the only variable changed is temperature. The reality of wild temperature change is that it

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[1] Meaning they maintain osmotic concentrations in their body fluids that are identical to the osmotic concentrations of the ambient medium. Osmoconformers have no mechanism to control osmosis.

[2] Osmoregulators as the name suggests regulate the osmotic concentration of their extracellular body fluid at a concentration different from the ambient medium

influences a range of other variables such as food availability, predator activity and water clarity. Consequently it is critical to understanding temperature (and any other environmental effects) to verifying these relationships exist also in the wild with co-varying factors. For example, the degree of synchrony between phytoplankton blooms and larval hatching is thought to be a primary determinant of early life stage survival for many species, the so-called 'match–mismatch' hypothesis (Cushing, 1972; (Burrow et al. 2011). Rising temperature may have significant effects on larval development and hatching.

Hatching

The timing of larval hatching varied interannually in the Dungeness crab and appears to be related to degree days during the egg incubation period. Larvae hatched later in 1997 and 2002 when temperatures were colder, and earlier in 1998 when temperatures were warmer (Park and Shirley 2008).

Development rates of *Paralithodes platypus* embryos held at higher than normal temperatures were not constant over time (Stevens et al. 2008). Moreover the crabs exhibited a slowing of development or diapause, resulting in the mean development times differing much less than would be predicted by temperature alone. Similar patterns were also exhibited by snow crab *Chionoecetes opilio* (Moriyasu and Lanteigne 1998) and Tanner crab (*C.bairdi*) (Swiney 2008). These findings suggest that there is flexibility in development rates to reduce variance in hatch timing caused by environmental variation.

Responses to temperature variation are not all fixed, and there is considerable flexibility or plasticity in the responses to temperature. For example, after 80% of the embryonic development time has elapsed in the American lobster, *Homarus americanus,* embryos appear to have an option choice of completing their development if they are in a suitable thermal environment (>11 °C), or remaining in stasis until the temperature is high enough (Helluy and Beltz 1991). Despite the halt on development the embryo is still metabolically active, using up valuable yolk reserves. The longer the embryos remain in stasis, the fewer the energy reserves available to the larvae upon hatching (Cowan et al. 2007).

Development

Larval development time, measured from hatching, generally declines with increasing temperature, where changes in temp at the low end of range are more consequential. Larval development in *Homaraus amercicanus* is optimised at temperatures above 12 °C (Templeman, 1938, Harding et al. 1983, MacKenzie 1988 in Cobb and Whale 1994). Development of *H. americanus* larvae continued at lower temperatures but at a greatly reduced rate (Figure 2). Similar rates of development occur along a temperature gradient in *H. gammarus* (Richards and Wickens 1979, Wickens and Beard 1991).

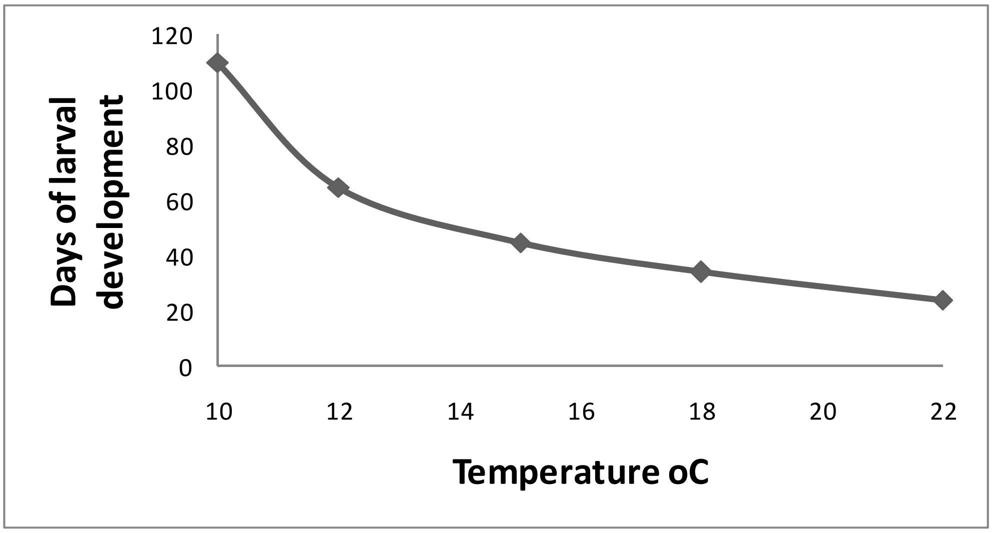

Figure 2. Rate of larval development in *Homarus americanus*, from (MacKenzie 1988).

The prolonged intermoult period at lower temperatures has been identified to increase the overall food consumption during the intermoult period in *J. edwardsii* and *Jasus verreauxi* phyllosoma compared to larvae reared at higher temperatures (Tong et al. 2000; Moss et al. 2001). Tong et al. (2000) also found that early to mid-stage *J. edwardsii* phyllosoma from the highest temperature treatments were smallest. They suggested that smaller larvae can be attributed to reduced food consumption combined with a higher metabolism at higher temperatures.

The first occurrence and the duration of the planktonic phase depends greatly on the temperature of the seawater, with larval hatching earlier when temperatures are warmer. In many species the number of days from hatching to moult into each larval stage decreases with increasing temperature, for example, *Scylla serrata* (Hamasaki 2003), *Cancer magsiter* (Sulkin et al. 1996). Settlement into the benthic juvenile phase occurs earlier when temperatures are warmer in *Cancer magister* (Sulkin and McKeen 1996).

Temperature effects on larval reptantia size vary. Increasing temperatures reduced larval size for a given developmental stage in, *Homarus americanus* (MacKenzie 1988) and *Jasus edwardsii* (Tong et al. 2000). However this pattern is not consistent for all crustacea. First stage larvae of *Cancer magister* were larger in the cooler offshore areas than in inshore waters, possibly due to low temperatures, although it could be due to food availability (Sulkin et al. 1996). *Jasus edwardsii* stage I phyllosoma kept at 18 °C had significantly reduced levels of eicosapentanoic acid (20:5*n*−3) and sterols compared to individuals kept at either (10.5 °C) or ambient (11.7 °C, range 9.5–13 °C). Ascorbic acid reserves were highest in the coldest incubated larvae. The results suggest a detrimental effect of warm incubation temperature during embryonic development on Stage I phyllosoma (Smith et al. 2002). As this temperature is far above ambient temperature this response might also be a stress response. In laboratory studies *Homaraus americanus* postlarval settlement was greater in an unstratified water column than in the presence of a thermocline (Boudreau et al. 1991). In the wild the thermocline may act as a natural barrier to settlement.

Numerous studies have demonstrated the profound influence of temperature on the development of reptantia larvae in terms of instar duration, morphology, feeding rate, size, incidence of deformity and survival (Johns 1981; Shirley et al. 1987). It is important to note that crustacean larvae do not usually experience temperature passively, they actively adjust their depth in response to both absolute temperature and rates of temperature change, e.g., *Rhithropanopeush arrisii* and *Neopanope sayi* (Forward 1990), *Pseudocarcinus gigas* (Gardner et al. 2004) The effect of temperature on vertical migration is covered in two comprehensive reviews (Sulkin 1984; Queiroga and Blanton 2005). Many of the above examples are drawn from aquaculture examples which have limited utility in defining thermal tolerances and expected field responses to temperatures as they often do not test the animals within its normal range, and do not contain enough information to account for geographic variation in broodstock source and therefore any local adaptation that might have occurred. Furthermore, they do not allow for behaviour of crustacean larvae to actively move in and out of water bodies of different temperatures.

Larvae and Postlarvae

Current systems and wind patterns on larvae

The patterns of the wind-driven and geostrophic currents influence delivery of larvae to suitable settlement habitat and thus influence larval duration, and successful settlement and recruitment. Most crustacean eggs are attached to the female and brooded until hatching, therefore the effect of currents and wind on eggs should be negligible. This section will only focus on the later life stages.

Ocean currents and wind pattern play an important role in the transition from the oceanic larval stages to the benthic stage in lobster and crabs, and hence successful recruitment to the fishery. As crustacean larvae have limited horizontal swimming capability (Ennis 1986), their position in the water is traditionally assumed to be primarily governed by currents. Postlarvae on the other hand appear to actively swim along the bottom. This divergence in movement is essential to the lobster and crab dispersal (Charmantierdaures and Charmantier 1991).

Spiny lobsters (Palinuridae) have a long and complex early life history, with a planktonic stage (phyllosoma) dispersed by oceanic currents for up to 24 months before settling as a puerulus in shallow coastal waters (Jeffs et al. 1999; Jeffs et al. 2001; Wells et al. 2001; Jeffs et al. 2002). *Homarus americanus* larvae concentrate in areas of downwelling, where currents come together (Aiken and Waddy 1986)) and in windrows, which are zones of strong surface motion (Harding et al. 1982). Similarly, *J. edwardsii* larvae concentrate in fronts at the interface of the East Australia Current (EAC) and slower moving water (Bruce et al. 2007). It is unclear whether larvae are actively or passively involved, and whether transport is a combination of passive horizontal movement and active vertical movement. Onshore wind may be responsible for larval transport from offshore locations to coastal sites, (Sheehy and Bannister 2002).

Current systems have a huge influence on fisheries production and species abundance. The relationship between settlement and current strength has been particularly well-studied in the western rock lobster *P. cygnus*, and this offers a good example of the relationship between broad-scale oceanic currents and settlement and condition of pueruli. In the warm waters of nutrient poor Leuwin current off Western Australia, invertebrate production dominates over finfish catches, whereas in other southern hemisphere eastern boundary currents (Humboldt, Benguela), where waters are cooler and nutrient rich, finfish production clearly dominates (Caputi et al. 1996). The strength of the Leuwin Current flow varies according to ENSO events, and are stronger during La Niña years and weaker during El Niño years (Pearce and Phillips 1988). The puerulus settlement rate of western rock lobster *Palinurus cynus* is also positively correlated with the strength of the Leuwin Current, and settlement is higher in La Niña years where Leuwin Current is stronger than during El Niño years with weaker Leuwin Current (Pearce and Phillips 1988; Caputi et al. 2001). Precisely how the Leuwin Current affects recruitment variation is not known in detail. The influence of the current on the larval life could be twofold. One explanation is that the increase in temperature associated with a stronger Leeuwin Current in April may improve growth and survival of the larvae (Caputi et al. 1996). As noted earlier, warmer waters would reduce the intermoult period thereby increasing the incremental growth and survival of the larvae. Alternatively the current may also aid larval retention by eddies and through transport of the later stages of larvae across the continental shelf into coastal reef nursery areas (Caputi et al. 1996). As pueruli swim across the predominant direction of flow of the Leeuwin and adjacent currents, their progress towards the near shore will be influenced by variations in the strength of the currents, as well as other environmental factors, such as prevailing westerly winds (Pearce and Phillips 1988; Caputi et al. 1995, 2001) and their proximity to eddies (Caputi et al. 2001), and of course the water temperature (Limbourn et al. 2009).

The strength of the Leeuwin Current (driven by ENSO events), the strength of the westerly winds and water temperature are three key environmental variables that affect the western rock lobster (*Panulirus cygnus*) fishery of lower western Western Australia (Caputi et al. 2003). As the puerulus stage relies on stored energy during its settlement onto near-shore habitats (Limbourn et al. 2009) it is particularly influenced by environmental effects. Warm-core eddies probably tend to have increased food supply for phyllosoma, which in return would increase lipid and protein content and quality in pueruli (Limbourn et al. 2009). Current patterns interact with biotic variables to influence recruitment magnitude and quality. Higher than average recruitment of *P. cygnus* during La Niña years suggested that nutrition may be an important driver of recruitment variation (Limbourn et al. 2009). Lipid content was lower in puerulus during ENSO years, when recruitment tended to be lower also (Limbourn et al. 2009). They detected strong seasonal patterns in fatty acid composition in La Niña years but not in El Niño years, underlining the importance of warm-core eddies to phyllosoma nutrition. Experimental studies have underlined that nutritional factors may be important in initiating metamorphosis of phyllosoma to the puerulus stage (Rotllant et al. 2001; McWilliam and Phillips 2007) providing sufficient energy reserves to sustain the cross shelf migration of pueruli (Fitzgibbon et al. 2013). Using an individual based larval transport model Griffin et al., (2001) concluded that the high variation in natural settlement could be primarily attributed to non-advective effects of fluctuations in the Leeuwin current, that is the effects of temperature and primary production.

Annual abundance of *Cancer magister* megalopae in Coos Bay, Oregon was significantly and negatively correlated to the date of the spring transition, i.e. recruitment was high when the spring transition was early (March) and low when it was late (May or later). As *C. magister* megalopa rely on the shoreward migration from the open ocean onto the continental shelf and it was assumed that the shoreward migration was assisted by spring transition when the California Current moves back onto the continental shelf. This influence of currents is directly impinging on the fishery for this species. The biomass of the adult population is determined by the success of their larvae is *C. magister*. The commercial catch landed in Coos Bay was strongly and positively correlated to the annual catch of megalopae settling four years earlier (Shanks and Roegner 2007). Interestingly, the opposite was observed for *Pagurus* spp., *Hemigrapsus* spp., and *Porcellanid* crab. The annual abundances of megalopae were significantly and positively correlated to the timing of the spring transition (i.e. stronger recruitment pulse in late spring transition years). As the larvae of those crab taxa remain close to shore, they may be carried offshore with the Davidson Current waters during the spring transition. In total the variation in the spring transition date, which marks a key annual shift in coastal currents, explained 90% of the annual variation in the annual abundance of megalopae of all 4 species of crabs investigated. Furthermore, as the spring transition occurs nearly simultaneously from Washington to Point Conception, California (Strub et al. 1987), the significant correlations between the timing of the spring transition and commercial catch can be observed over the entire West Coast (1700km long). As the number of megalopae returning to shore determined future commercial catch of Dungeness crabs and the timing of the spring transition determined megalopae abundance over a wide special scale; the timing of the spring transition has potential to serve as an indicator for commercial catch.

Studies of the influence of the California current on recruitment of the Dungeness crab (*Cancer magister*) have identified correlations between recruitment and variables indicating ENSO conditions and wind-forced larval transport. Variability in recruitment of both crabs appears to be driven by daily temporal variability in upwelling winds and 100-km spatial variability in coastal topography. Interannual recruitment variability appears to depend on ENSO-related biological productivity and larval transport, which are not completely understood (Botsford 2001). When abundance time series were compared to mean daily wind stress, maximum daily tidal range, and mean daily temperature residual, variation in wind stress had little effect on crab megalopae abundance in

Cancer magister, *C. productus, C. oregonensis*, *Hemigrapsus oregonensis* and *Pachygrapsus crassipes*. Crab recruitment appeared to be primarily controlled by tidal forcing for these species (Roegner et al. 2007).

Tilburg et al. (2005) developed a coupled model which quantified the effects of several mechanisms on larval transport and recruitment of the blue crab (*Callinectes sapidus*) in Delaware Bay and hindcast actual larval settlement for a four-year period. Timing of larval settlement was primarily driven by wind stress, however the model failed to fit observations in 1989, which indicated that small-scale physical events as well as larval behaviour and confounding factors not reproduced in the model all acted together to determine the timing and pulse of larval settlement (Tilburg et al. 2005). Onshore winds and sea surface temperature were correlated to settlement of the European lobster *Homarus gammarus* (Sheehy and Bannister 2002).

Salinity on Larvae and Postlarvae

Many larvae are hyperosmoconformers and can actively avoid changes in salinity. Shore crabs, such as *Libinia emarginata* can weakly osmoregulate as larvae, which is an unusual ability early in ontogeny (Charmantier 1998). Survival of larvae is often reduced at lower salinities for stenohaline species. *Homarus americanus* could not be cultured to stage 4 below 17ppt (Templeman 1936). Rapid osmotic adjustment is important to planktonic crustacean larvae as exposure to low salinity surface water following heavy rainfall. For instance in *Homaraus americanus* stage-three larvae adapted to diluted water in three hours and stage-four larvae in six hours. Stage-4 better had survival than stage-3 and minimum salinity for survival 12.5 (Charmantier et al. 1988). Salinity tolerance in adults and juveniles is determined largely by efficient regulation of the volume, and often the osmolarity, of the body fluids by specialised branchial epithelia and excretory organs (Taylor and Seneviratna 2005).

Natural mortality

Survival of Juveniles and Adults

After a long larval development in pelagic waters crustacean larval settle from the phyllosoma or megalopa into benthic juveniles, in habitats often similar to their adult habitat. For many species this is a site-attached or sedentary phase and so the occurrence of a species in a region determined by the temperature regime, as well as appropriate habitat. In an elegant test of barriers to their natural range of Dungeness crab (*Cancer magister*), reasons for their absence of from a suitable habitat with an adequate supply of larvae was identified (Sulkin et al. 1996). The authors raised late stage larvae and juveniles at the range of temperatures reflecting those from the area they were absent. Megalopal survival was not affected by temperature, however, juvenile crabs had reduced growth rate and high mortality at 22 °C, supporting the hypothesis that commercial crab fishery stocks in the region are absent because of high mortality of newly settled juveniles where summer water temperatures exceed 18°C (Sulkin et al. 1996). Moult increment in juvenile *C. magister* did not vary significantly between 5°C and 15°C, most likely because Dungeness crabs are exposed to this temperature range along their geographic range (Kondzela and Shirley 1993). Testing a similar hypothesis on minimum temperature thresholds rather than maximum thresholds, winter mortality of Chesapeake Bay blue crabs (*Callinectes sapidus*) was measured in Chesapeake Bay to assess whether harsh winter conditions could be a significant source of stock loss (Rome et al. 2005). *C. sapidus* suffered relatively low winter morality rates (≤3%) during five out of eight winters, when bottom water temperature in February was at or above the 8-year average (3.4 °C). In contrast, during the other two years when bottom water temperature fell below the February average, annual mortality rates increased to 6.0-14.5%. Peak mortality rates in the coldest regions of Chesapeake Bay corroborated these findings. Similar thresholds were identified in the laboratory. Here the highest mortality occurred in the lowest temperature (1°C) and salinity (8 ppt) treatments (Rome et al. 2005). Larger and particularly female crabs appeared to be most vulnerable to these stressful conditions. Mature females were less tolerant than juvenile crabs and of the juvenile stages, recruits (<15 mm carapace width) were least tolerant to winter conditions. In the early 1980's an increase in survival and growth rates of juvenile *Homarus americanus* was attributed to an increasing sea temperatures near Halifax, which gave rise to increased recruitment to the fishery throughout coastal Nova Scotia during the mid- to late 1980's (Campbell et al. 1991).

In laboratory experiments *Callinectes sapidus* were capable of maintaining their metabolic rate between 20 and 27 °C, an evidence of acclimation (Leffler 1972). Although it appears that they still make adjustments at higher temperatures, their metabolic rate increases with temperature above 27 °C (Leffler 1972). Although they currently also live in cold temperate, the evolutionary origin of *Callinectes sapidus* is actually in the tropics, which may assist their adaptability to a range of temperatures (Rome et al. 2005).

Life span was shortened and total body size decreased with increasing temperature in crabs, *Portunus trituberculatus* (Kim et al.), *Cancer magister* (Terwilliger and Dumler 2001) *Callinectes sapidus* (Fisher 1999) (Darnell et al. 2009) *Portunus pelagicus* (De Lestang et al. 2003) *Paralithodes camtschatica* (Stevens 1990) and lobsters including *Homarus americanus*, (Landers Jr et al. 2001) and *Panulirus cygnus* (Johnston et al. 2008).

Salinity on Juveniles and adults

Because less saline water are less dense and overlay more saline waters, benthic juvenile and adult stages rarely encounter hyposaline conditions (Aiken and Waddy 1986). Juveniles and adults tend to be osmoconformers, but hyperosmoregulation occurs at lower spectra of the salinity tolerance range (Charmeantier et al. 1984a, Dall 1970). Juvenile *H. gammarus* require 24 hours (Charmantier et al. 1984) and adults 75 hours (Dall 1970) to adjust to changes in salinity. Low salinity is more stressful at higher temperatures (Jury 1992), and the combination of temperature and salinity change has a synergistic effect. For example, for *Homarus americanus* salinity was lethal at 6 ppt at 5 °C and 16.4 ppt 25˚C (Mcleese 1956). Lobsters are capable of detecting salinities and prefer higher (20–25) over lower salinities (10–15) and appear to avoid these.

There is also evidence that suggests that crabs and lobsters mature at smaller sizes when salinity is higher, e.g., *Callinectes sapidus* (Fisher 1999). Temperature interacts with salinity tolerance and can improve salinity tolerance. For example, the mud crab *Scylla serrata* larvae have a broader salinity tolerance when they are held at optimum temperatures of 21 °C (Nurdiani and Zeng 2007). Hartnoll reviewed the effect of salinity on adult growth and concluded there were minimal effects of a range of salinities on growth of crustacea (Hartnoll 1982).

Catchability and Catch Rates

Catchability is the probability of an animal being captured by a randomly applied unit (e.g., trap), and there is often an assumption in estimates of biomass based on catch per unit effort that catchability remains constant (Morgan 1974). Factors other than abundance influence catch rates, and are often assumed to act as a time-varying multiplicative factor on abundance known as catchability (ArreguinSanchez 1996). Catchability can vary with population density, and is assumed to decrease as the population density increases.

$$c/f = qD,$$

where c/f is catch rate, number of animals per trap, D= absolute density, animals per square metre, and q is the catchability coefficient, square metres per trap (Miller 1990). Understanding the environmental factors affecting catch rates provides a way of standardising these catch rates to provide a more reliable abundance index and hence an improved stock assessment and a more effective management of stocks (Srisurichan et al. 2005). There are other observed changes in catchability that are often not related to changes in stock abundance. In the section we will examine evidence of changes in catchability in lobsters related to environmental variation.

The catchability coefficient of a number of lobsters are influenced by a variety of both environmental and endogenous parameters, on an annual basis as well as in shorter-term changes. Environmental factors can interact to influence catchability. Monthly catchability (q) of a population of the western rock lobster (*Panulirus cygnus*) was calculated using measures of catch, effort, population density, and area of reef. Catchability increased with increasing water temperature and salinity in adults and juveniles, and decreased with percentage of lobsters in pre-moult condition ($P < 0.001$). These relationships offer a method of adjusting the catchability coefficient, leading to an improved stock assessment for this species (Chittleborough 1970; Morgan 1974). Similarly, catchability and activity rates increased with water temperature for *Homarus americanus* throughout the range of temperatures normally encountered by the lobster (McLeese and Wilder 1958). Activity increases with water temperature in *Homarus gammurus* (Smith et al. 1999). Habitat heterogeneity in *Homarus americanus* influenced catchability, with decreased catchability in higher-relief sites compared to low-relief sites, possibly due to increased shelter or decreased dispersal of bait odour plume (Tremblay and Smith 2001).

Wind and catchability

Wind also appears to have an effect on catchability of *Homarus americanus*, principally due to its influence on ocean bottom temperatures, consistent with the classical Ekman response (Drinkwater et al. 2006). Eastward wind produces warmer water by forcing the warmer upper layers shoreward and causing downwelling, whereas westward winds causes upwelling of colder water, hence resulting in colder bottom temperatures and reduced lobster catchability (Drinkwater et al. 2006).

Temperature and catchability

Catchability of decapods often increases with temperature (Table 1) because the activity and appetite of the target species, and the rate of diffusion of the bait molecules increase with temperature (Morrissy 1975). In the short term, fishers report that day-to-day catch rates are variously influenced by type of bait, sea swell, wind strength, tidal movement and water turbidity, although quantifying changes in catchability from fishermen's data would be extremely difficult (Koeller 1999).

Catchability in some species of lobsters is more complex than abiotic environmental effects alone. In *Jasus edwardsii*, catchability was influenced by water temperature (Ziegler et al. 2002) but was more strongly influenced by biotic effects such as moulting, mating and density (Ziegler et al. 2003; Ziegler et al. 2004)(Table

1). There is often higher catchability of larger crustaceans, e.g., *Homarus americanus* and *Cancer irroratus* (Miller 1990), *Jasus edwardsii* (Frusher and Hoenig 2001), *J. lalandii* (Pollock and De B. Beyers 1979) possibly due to the exclusion of smaller lobsters by larger lobster in pots (Scrivener 1971; Ihde et al. 2006). Catchability differed markedly between legal-sized male and female *J. edwardsii*, although catchability of both sexes generally declined in winter and was elevated in summer.

For males, water temperature was the major factor in determining seasonal catchability, and most models in which water temperature had been fitted to catchability estimates performed better when this was done prior, rather than simultaneously, to fitting the moulting and mating components. For females, water temperature improved the model fits in all models, directly as a major component and indirectly by influencing the effects of moulting and mating. Mean monthly water temperature described 9–52% of the seasonal variation in catchability in different years in the south, while in the north water temperature accounted for only 1–19% of the seasonal variation in catchability. The strength of the temperature effect on catchability varied regionally, and was stronger where temperature was lower (Ziegler et al. 2003).

Kanicruk (1980) reviewed the impact of lunar cycle on a number of spiny lobster species and indicated that the activity and catch rates of *P. japonicus* and *P. argus* were affected by the lunar cycle, but *P. japonicas* were also affected by water temperature, lunar cycle and intensity of ocean waves (Yamakawa et al. 1994). In contrast, Loeztegui et al found no correlation between lunar cycle and catchability in *P. argus* from the Gulf of Batabano, Cuba (Lopeztegui et al. 2011). The effects of moon phase may well be a local issue with no consistent trends between fisheries.

Catch rates of *P. cygnus* had a cyclical pattern in the series compared to the moon phase (Srisurichan et al. 2005). In general, the cyclical pattern had its minimum during the full moon period and maxima near the new moon period. The cycles of the legal-sized lobsters in shallow water appeared to show the clearest patterns compared with those of the legal-sized lobsters in deep water, or compared to undersized lobsters (Srisurichan et al. 2005). The swell had an impact on the catch rates of legal-sized lobsters in both shallow and deep waters (except for shallows in one of the three zones) with significant lags mostly at 1 day (Srisurichan et al. 2005). The impact of the swell on the catch rates in shallow water was stronger than that on the catch rates in deep water, possibly due to swell disturbing the bottom and increasing the availability of food or providing greater protection through increased turbidity. Effects were also strongly seasonal with null effects in November to January (Srisurichan et al. 2005).

A depletion model for *Panulirus cygnus* was more reliable when catchability between months was accounted for (Wright et al. 2006). Temperature and swell corrected catch rates greatly improved the linearity and reliability of depletion estimation and if the correction for water temperature change is not undertaken it results in a lower estimate of residual biomass and higher estimate of exploitation and catchability (Wright et al. 2006). Catchability estimates may also be affected by the spatial distribution of *P. cygnus* abundance and hence the spatial distribution of the fleet targeting the lobsters. If the fleet is concentrated over a small spatial area in one year owing to the concentration of the stock it may result in an increase in catchability for the year (Wright et al. 2006). Catchability of *P. cygnus* was enhanced with increases in swell conditions (Srisurichan et al. 2005), and this may bias the parameter estimates if not taken into account. Moon phase is a third factor affecting catchability (Table 1) and the use of monthly catch rates mostly eliminates this impact (Wright et al. 2006). Increased sea swell increased catch rate in *P. cygnus* and *P. japonicas*, but there is no similar relationship described for *P. argus* and *J. edwardsii* (Table 1).

TABLE 1. CHANGES IN CATCHABILITY WITH ENVIRONMENTAL CONDITIONS

Species	**Increase water temp**	**Increase salinity**	**% in pre-moult condition**	**Increasing swell**	**Increasing wind speed**	**Full moon**	**increase in population density**	**reference**
Panulirus cygnus	Increase	increase	decrease	Increase		decrease		(Morgan 1974; Wright et al. 2006; Srisurichan et al. 2005)
P. Cygnus juv	Increase						increase	(Chittleborough 1970; Wright et al. 2006)
P. argus						null		(Lopeztegui et al. 2011)
P. japonicus				Increase				(Yamakawa et al. 1994)
Jasus edwardsii	increase, decrease			Decrease		null, increase	decrease	(Ziegler et al. 2002; Ziegler et al. 2003; Ziegler et al. 2004; Ihde et al. 2006; Feenstra 2012)
Homarus americanus	increase, decrease				decrease, null		decrease	(McLeese and Wilder 1958; Koeller 1999; Drinkwater et al. 2006; Tremblay et al. 2006; Pickering et al. 2010; Courchene and Stokesbury 2011)
Homarus gammurus	Increase							(Schmalenbach 2009)

Disease

As marine ecosystems are degraded, the impact of disease is on the increase (Hughes 1994). Multiple stressors in the marine environment can increase the frequency of disease and the severity of its impacts as resilience is reduced by multiple stressors of climate change, pollution and loss of habitat (Wernberg et al. 2011). Disease will limit food from future crustacean aquaculture and fisheries (Stentiford et al. 2012). Crustacean fisheries suffer direct mortality caused by pathogens, and indirect effects such as limited growth, reproduction and reduced value due to reduced moulting and undesirable appearances (Shields 2012).

The potential risk of disease is expected to increase with higher temperatures (Pearce and Belcom 2005) and climate change (Stentiford et al. 2012). In the summer of 2002 Long Island Sound populations of the American lobster (*Homarus americanus*) declined due to a new disease, excretory calcinosis, which is characterized by metastatic calcium deposition in the gills and antenna1 glands, resulting in fatal respiratory failure due to reduced effective surface area of the gills (Dove et al. 2004). As no significant pathogens were observed, the occurrence of the disease was attributed to prolonged thermal stress caused by a long-term trend of increasing bottom water temperatures (Dove et al. 2004). Experimental work on the effect of thermal stress was conducted by holding one group at 16 °C, representative of late spring (controls), and the other group at 23 °C, representative of late summer/early fall (treatments) (Dove et al. 2005). The treatment group showed a depression of haemolymph pH and reduced phagocytic activity, which are consistent with hyperthermic acidosis and lower immunocompetence (Dove et al. 2005). As the experimental temperatures cover the current annual variability, Long Island Sound is already a stressful environment for *H. americanus*, perhaps becoming inhospitable in the long-term.

Another disease, the epizoic shell disease, affecting *Homarus americanus* has also been linked to increasing bottom water temperatures, although this one is bacterial in origin (Glenn and Pugh 2006). As both the shell disease occurrence and the bottom water temperature from Massachusetts Bay increase from North to South, it was postulated that temperature may act independently or synergistically on the disease prevalence (Glenn and Pugh 2006). Warmer temperatures favour bacterial growth. As females mature faster in warmer waters and intermoult duration is increased after maturity, exposure time to disease-causing bacteria would by increased by higher temperatures. Disease incidence is highest in May and June, before the major moulting, and lowest in August after most lobsters have moulted (Glenn and Pugh 2006). The effects of this disease to post-settlement mortality were strong enough that it obscured the effect of variable recruitment on cohort strength or population size (Wahle et al. 2009).

The first records of luminous *vibriosis* in spiny lobsters was observed in *Jasus verreauxi* phyllosoma (Diggles et al. 2000). The original outbreak followed an increase in water temperature from 19 to 23 °C, which is consistent with *Vibrio harveyi* acting as a pathogen of crustaceans at warmer water temperatures (>22 °C). However, the second disease outbreak showed that luminous vibriosis could occur at 20°C without an increase in water temperature and even at water temperatures as low as 16 °C (Diggles et al. 2000). Higher temperatures were also proposed as a major factor in the intensity of an infection caused by a parasitic dinoflagellate of the genus *Hematodinium*, which affects the *Cancer pagurus* fishery in Ireland (Chualáin et al. 2009). An increase in temperature increases disease risk through a range of mechanisms, including bacterial infection, parasitic dinoflagellates and acidosis.

Climate change

Climate change is modifying temperature, currents, wind, timing and quality of plankton blooms and water chemistry. Previous sections of this review have described the response of crustaceans to environmental change within the daily, seasonal and annual cycles crustaceans were likely to experience. This section expands that to address the effects of longer term changes to environmental variables through climate change. We will provide an overview of some of the observed and predicted climate change effects on crustaceans. For an extensive review on the effects of climate change on fisheries see Pörtner and Peck (2010).

Water temperature

Climate change is shifting temperature beyond the thermal envelope many species are adapted to. Increasing water temperatures can be expected to affect other biological parameters such as moult frequency, growth, and natural mortality, puerulus settlement, catchability, females moulting from setose to non-setose, timing of moults, and peak catch rates. Global average air temperature and consequently sea surface temperature have increased by 0.4 - 0.8˚C in the last century (Harley et al. 2006a). These changes in averages do not necessarily explain the scale of the effects of temperature change throughout the globe. Although tropical and polar organisms may experience a lower numerical rate of rise in temperature than the east coast of Australia for instance, they might be affected by warming temperatures by a greater extent because they are naturally acclimatized to a comparatively narrow range of temperature. Ongoing climate change is responsible for poleward shifts in the distribution of marine species (Hampe Petit 2005). Evaluating the condition of the 'rear-edge' populations may provide indications for the future of current population centres.

Higher water temperatures are also likely to increase lobster and crab activity, which should increase catchability and hence improve fishing efficiency (Ziegler et al. 2003; Caputi et al. 2010). Often catch rates are used as proxy for abundance. To counter the temperature effects of climate change, the stock assessment for effort-controlled fisheries would have to take such an increase in harvest rates into account and reduce the fishing effort appropriately in order to maintain a sustainable fishery.

In the North Sea annual mean surface water temperatures have risen by almost 1.5 °C from 1962 to 2005 (Wiltshire et al. 2008), and warming has been most pronounced in winter (e.g., Franke et al. 1999). Climate change scenarios forecast warming to continue, with a further increase in North Sea water temperature by 2–3 °C over the 21st century (IPCC 2007). Laboratory tests of these effects on European lobster *H. gammarus* suggest the 2 °C increase in water temperature during the incubation period reduces incubation time (Schmalenbach and Franke 2010a). Larval development in turn will commence at lower seasonal temperatures and will need more time to metamorphosis which prolongs the high risk larval period, increasing exposure to predators and subsequently increasing mortality.

A climate regime shift in the North Pacific in 1989 is believed to have caused a dramatic decline in the catch of the Hawaiian spiny lobster (*Panulirus marginatus*) (Polovina et al. 1999; Hare and Mantua 2000; Polovina 2005).

Ecosystem modelling would assess these effects for other species, assessing the particular windows for sensitive stages such as egg extrusion, hatching and larval development, as well as the inherent plasticity in each stage. Plasticity and potential adaptability to climate change can be assessed by examining the range of windows for each stage throughout the geographic range of the species. Furthermore long-term biological time series (of at least 30–35 years) are required in order to detect significant changes in climate and stock abundance and distribution and other biological parameters. Understanding long-term changes in trophic chains will be crucial for a successful ecosystem-based approach to the future management of North Sea fisheries and other fisheries at a time of climate change (Lindley and Kirby 2010).

Match-mismatch

Hatching too early or too late, as a result of climate change could have a serious consequences on decapod larvae by missing primary peak of zooplankton such as diatom blooms, as per the ''match-mismatch'' hypothesis by Cushing (Cushing 1972; Cushing 1990). All organisms have generally evolved to coincide reproduction with peak availability of suitable food for survival and development of the offspring. Lobsters and crabs do not have endogenous mechanisms to delay larval hatching to coincide with optimal external conditions for larval development (Schmalenbach and Franke 2010b), so it is predicted that an increasing mismatch between larval peak appearance and optimal food conditions will have a negative effects on growth and reproduction (Schmalenbach and Franke 2010a).

Case study 1: Western rock lobster

Rising sea water temperatures over the last 35 years have widely been attributed to a decrease in the size of maturity and the size of *Panulirus cygnus* migrating to deep water. As a result the abundance of undersized and legal-sized lobsters in deep water has increased relative to shallow water. Although a decline in size at maturity would increase protection of breeding stock, the end result would be a lower maximum size due to an increase in growth rate before maturity followed by a decrease in growth after maturity (Caputi et al. 2010). Increasing water temperatures also affects timing of reproduction. Larger, and presumably older lobster and crab females spawn longer and later into the breeding season than smaller females in both western rock lobster (Lestang and Melville-Smith 2006) and red king crab (Stevens and Swiney 2007). The longer spawning periods of older females may be an adaptation to increase the concurrence of their larvae with plankton production cycles, which have also shifted with climate change (Caputi et al. 2010). This strategy would be expected to improve the chances of progeny survival. However, with decrease in size at maturity, the mean size at which females carry several broods per spawning season has declined (de Lestang and Melville-Smith 2006). The enhanced juvenile growth rate of juveniles may be compensated by at maturity and a smaller asymptotic maximum size (Caputi et al. 2010). The onset of maturity at a smaller size could therefore have a negative effect on the overall growth rate and the overall stock productivity.

Rising temperatures may have positive effects on the larval development, especially in higher latitudes of species distribution, conversely the opposite be true at the lower latitudes, reducing population abundances where temperature is already a limiting factor (Caputi et al. 2010). The net result is that many lobster and crabs may shift and even contract their geographic range.

Case study 2: Tasmanian rock lobster fishery

The range of the Tasmanian rock lobster (*Jasus edwardsii*) fishery covers the interface of the East Australian Current and the Southern Ocean. While the rest of the species has a larger range, the Tasmanian *J. edwardsii* from the east coast of Tasmania have been examined in closer detail due to the congruence of the current systems. The East Coast of Australia is experiencing ocean warming with an increase in surface temperature by 2.28 °C per century (Ridgway 2007a). Not only is the Southern Ocean predicted to experience the fastest decline in pH (Fabry et al. 2008) but the rate of global warming in the Tasman Sea is estimated at 2.5 times the global average (Suppiah et al. 2007). A climate change assessment report by Pecl et al (2009) the current stock assessment model with biophysical models predicting the changes to water temperatures and currents. Climate models predict a strengthening of the East Australia Current (EAC), which would bring warmer water further south along the eastern Tasmanian coast (Ridgway 2007b). East-coast puerulus settlement depends on the position of the sub-tropical convergence (STC), where the warm EAC meets the cold Southern Ocean (Bruce et al. 2007). Recent climate change models projections including the effect of temperature on growth and recruitment, predict an initial gain in biomass due to the positive correlation between temperature and growth rate. Due to the increased strength of the EAC, growth rates in southern regions will increase mostly. As a result of the penetration of the STC declines in the north-eastern and eastern regions and thus puerulus settlement in is likely to decline, adversely affecting recruitment (Pecl et al. 2009). Consequently there may be a trade-off between opposing short-term increases in lobster growth and long-term recruitment decline. Climate change may also result in higher abundance of lobster predators (such as octopus (Pecl and Jackson 2008), although octopus predation is such a minor part of mortality (natural and fishing) in rock lobster we do not expect this change to be significant.

One of the limitations of this kind of report (Pecl et al. 2009) is that it is projections and is not field-tested. We undertook a large-scale translocation experiment that moved 30,000 pale-coloured, slow-growing lobsters from deep cold water to inshore areas along the East coast of Tasmania where growth is faster. For the lobsters at the southern extent of their range (rear edge) this translocation represented a change in mean water temperature that reflects changes predicted by climate scenarios for 50 years hence (IPCC 2007). Lobsters growth increased beyond that of the resident inshore lobsters within the first moult (Chandrapavan et al. 2010; Green et al. 2010), resulting in an improved reproductive output (Green et al. 2010). Lobsters quickly established new residences (Green et al. in press), and nutritional condition of the deep water lobsters also improved (Chandrapavan et al. 2009). These positive changes suggest that southern rock lobster is plastic enough to accommodate a changing climate in at least some parts of its range.

Other ecosystem changes are occurring with shifts in the EAC and are apparent already. The southerly extension of the EAC has extended the range and expansion of *Centrostephaus rodgersii*, the long-spined sea urchin on Tasmanian rocky reefs (Ling et al. 2009). There are barren-forming urchins which denude the macroalgae from the rocky reefs they inhabit. This phase-shift has the potential to have a negative cascading effect on the *J. edwardsii* fishery as well as the valuable abalone fisheries (Ling et al. 2009). It is currently unclear whether the water temperature has risen enough for the larvae to survive, but if it has then this is a long-term problem. This example highlights the synergistic effects of climate change with human induced stressors, which threatens to limit the adaptive capacity of these systems (Ling et al. 2009). In the oceans, climate change and overfishing pose two of the greatest challenges to the structure and functioning of marine ecosystems.

Ocean acidification

As a result of increasing carbon dioxide (CO_2) emissions, the world's oceans are slowly becoming more acidic (Caldeira and Wickett 2003; Orr et al. 2005). During the last century, the pH of the oceans has dropped by ~0.1 units, an equivalent to a 25% increase in acidity, and models predict pH to decline by 0.2 to 0.4 units by the year 2100 (Caldeira and Wickett 2003; Dupont et al. 2008). It may not sound like much, but already the detrimental effects are manifest in marine calcifers, for example (Mayor et al. 2007; Dupont et al. 2008; Arnold et al. 2009; Pelejero et al. 2010; Sheppard Brennand et al. 2010; Walther et al. 2010). Manipulative experiments on marine calcifiers, including echinoderm, bivalve, coral and crustacean species, have shown that ocean acidification negatively affects growth, physiology, fertilization, cleavage, larval development, settlement and reproductive success (Kurihara 2008). Manipulative experiments on fish larvae indicate a change in behavior and a loss in navigational ability which would seriously interfere with finding suitable settlement habitat (Munday et al. 2009; Munday et al. 2010) and detecting predators (Dixson et al. 2010) or prey (Cripps et al. 2011) although not all species are affected by these changes (Munday et al. 2011). If ocean acidification impairs larval survival rate, as well as reproductive success, the population abundance, distribution and community structure will adversely be affected.

Early life-history stages might be most vulnerable to CO_2-induced ocean acidification (Portner and Farrell 2008). For example, Mayor et al. (2007) observed significantly reduced hatching of *Calanus finmarchicus* larvae at a pH of 6.95 (Mayor et al. 2007). Crustaceans with long larval stages, such as *J. edwardsii* (12–24 months), and long generation times (*Pseudocarcinus gigas*) are especially vulnerable to ocean acidification, and perhaps to a greater extent than other species with shorter larval and generation cycles. Species with long generation times are assumed less likely to adapt to changing environments. It is likely species at extreme temperatures living close of temperature limited biogeography (i.e. latitudinal gradient) will be more sensitive to ocean acidification (Portner and Farrell 2008).

Specific effects of increased acidification on crustaceans have been recorded. Dry weight of European lobster larvae, *Homarus gammarus,* decreased at exposures of 1200 ppm CO_2, but no differences were detected in the period of planktonic development (Arnold et al. 2009). Presumably, CO_2 first affects larval growth before the duration of development is extended. Spider crab (*Hyas araneus*) larvae had a similar response (Walther et al. 2010), where dry weight and C/N ratio decreased at 710 ppm CO_2. Prior to moulting, larval metabolism appears to switch from lipid storage to an increasing production of protein (enzymes and structural proteins relevant during moulting), which is reflected in decreasing C/N ratios (Anger and Harms 1990). CO_2 might affect these metabolic processes, e.g. through metabolic depression (Portner et al. 2004). It may thereby reduce the C/N ratios and dry weight. Lower dry weight might also indicate a thinner and less calcified exoskeleton (Arnold et al. 2009), causing greater susceptibility to predators and disease. Measuring C:N ratio also enables to separate temperature effect from CO_2 effect (Walther et al. 2010).

Increased CO_2 narrows the thermal window in the spider crab, *Hyas araneus* and the edible crab *C. pagurus* with an as yet unclear mechanistic background (Metzger et al. 2007; Walther et al. 2009; Walther et al. 2010). High CO_2 concentrations caused a delay in development in *Hyas araneus* (Walther et al. 2010). The question arises whether a threshold concentration exists above which larval development and growth is disturbed. Walther et al. (2010) identified the megalopa stage as well as reproducing females as the bottle neck in the life cycle of *H. araneus* as the physiological tolerance range is smallest for those stages.

The ultimate ecological challenge is to predict how natural ecosystems respond to future environmental change. However complex and unexpected responses, specific to unprecedented climatic conditions, are likely to occur (Harley et al. 2006b). As different pressures may act synergistically (e.g. fishing pressure and climate change, temperature and $p\mathrm{CO}_2$), the complex components of the ecosystem will respond to climate change at different rates and in various ways. What is apparent from the early section on the other environmental variables in this review is that while there are clear trends when variables are assessed independently, such as temperature increasing growth rates of all life stages, there are species specific lethal limits to this. When environmental variables are assessed in combination the effects are often synergistic, the impacts of the response may be negative or positive and the direction and the magnitude are species specific. Many species may possess the mechanisms to adapt to climate change, however there are limits to phenotypic plasticity. Realistic predictions may be erroneous if coarse spatial and temporal data are used for large scale modelling and environmental heterogeneity can provide suitable habitat despite predictions cover a large spatial indicating species' extinction (Fuller et al. 2010).

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