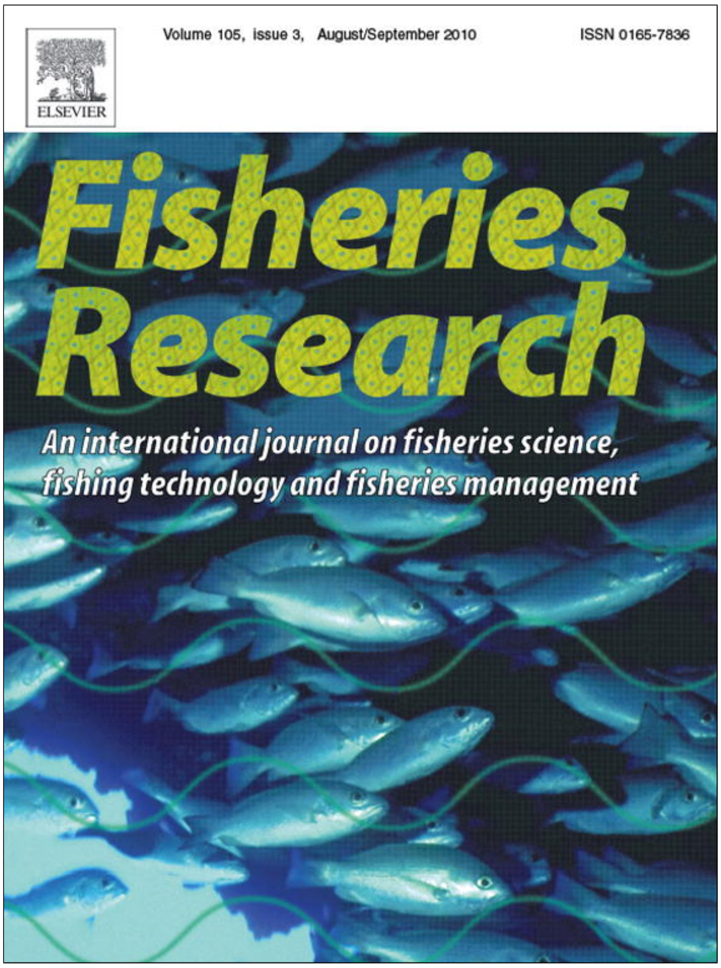
Volume 105, issue 3, August/September 2010
ISSN 0165-7836
ELSEVIER
Fisheries Research
An international journal on fisheries science, fishing technology and fisheries management

Fisheries Research 105 (2010) 163–171

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

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

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ARTICLE INFO

Article history:
Received 7 January 2010
Received in revised form 1 April 2010
Accepted 1 April 2010

Keywords:
Southern rock lobster
Jasus edwardsii
Recruitment
Fishery
Management

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 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 indicate 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.

1. 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 3500 to 4000 tonnes with an estimated gross commercial value of ~AUS$200 million (Knight and Tsolos, 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 typ-

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doi:10.1016/j.fishres.2010.04.001

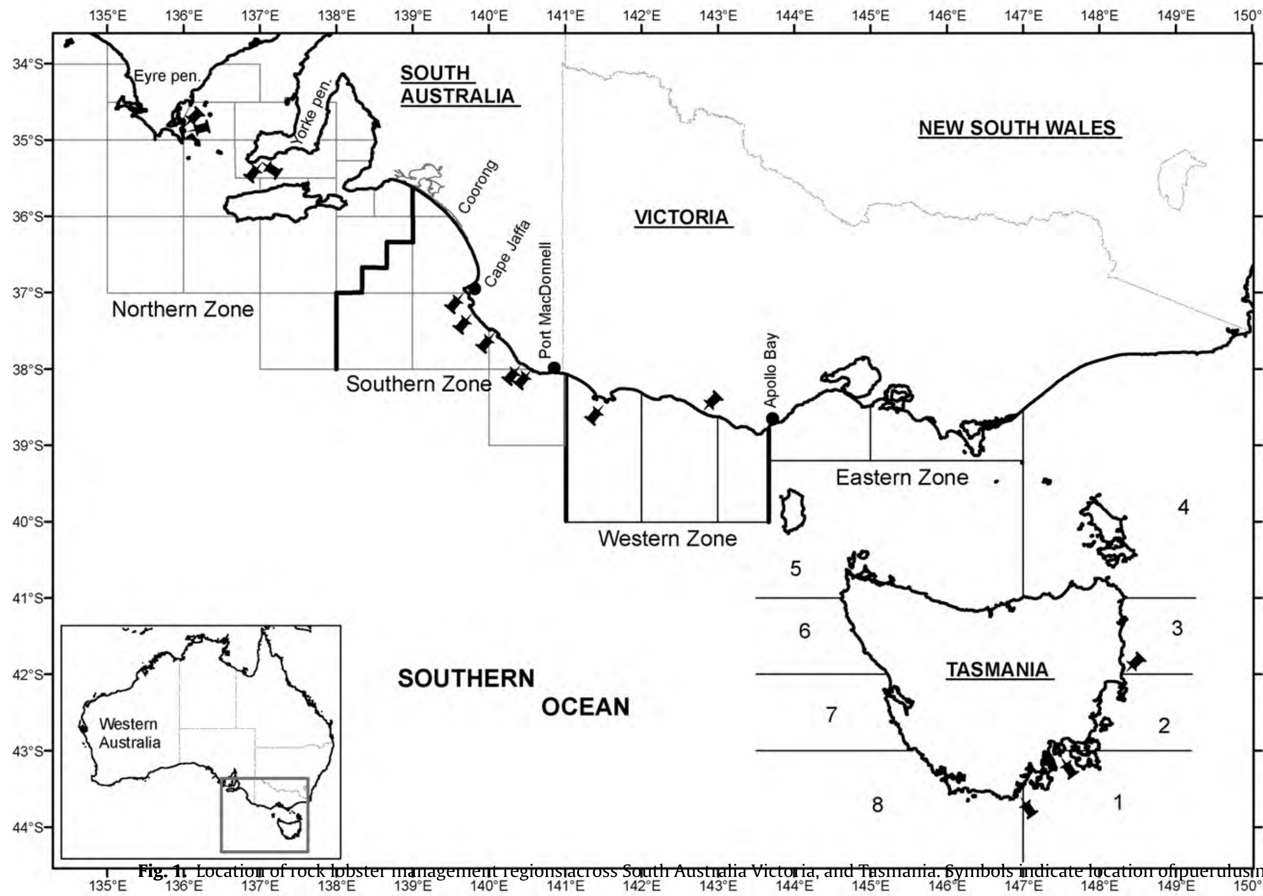

Fig. 1. Location of rock lobster management regions across South Australia Victoria, and Tasmania. Symbols indicate location of puerulus monitoring sites.

ically 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,b). 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.

2. Methodology

2.1. 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 3–6) 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.

2.2. 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,

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 differences in the spatial values of biological parameters.

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

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:

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

where $\bar{R}[s]$ is the mean (time-independent) recruitment level in each subregion, $\varepsilon[y, s]$ 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 $\bar{R}[s]$.

2.3. 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.

2.4. 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.

2.5. 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.

2.6. 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 to 1996 across the fishery (Linnane et al., 2005). The second utilised tag returns from an ongoing annual fishery-independent monitoring survey from 2006 to 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.

3. Results

3.1. 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

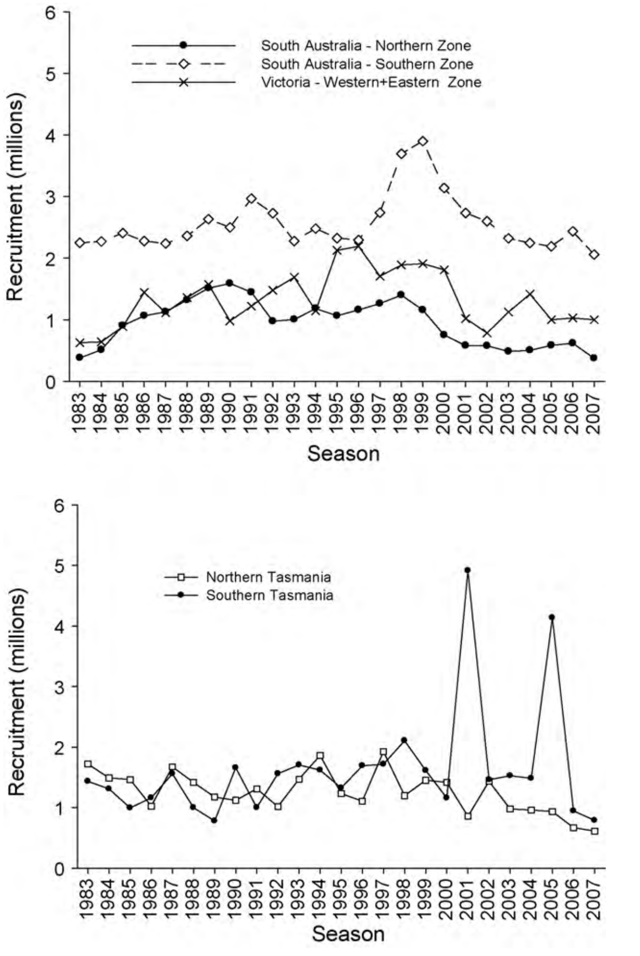

Fig. 2. Trends in maximum likelihood estimates of recruitment across South Australia, Victoria (top) and Tasmania (bottom) from 1983 to 2007.

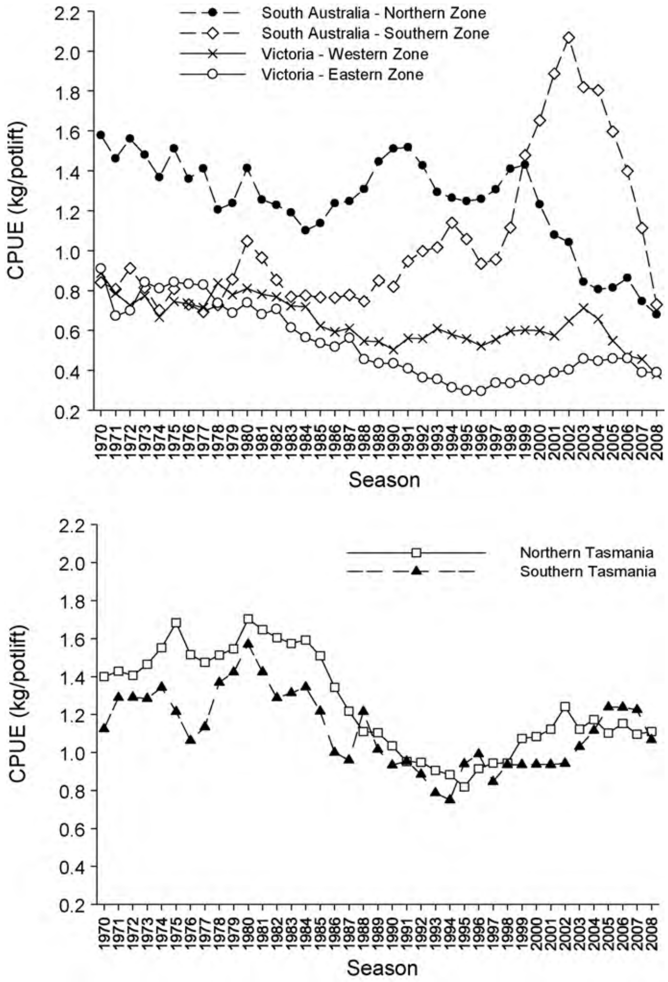

Fig. 3. Trends in catch per unit effort (CPUE) across South Australia, Victoria (top) and Tasmania (bottom) from 1970 to 2008.

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.

3.2. *Commercial catch rates*

Recent decreases in recruitment levels have translated to declines in commercial catch rates in most fisheries across south-eastern Australia (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.

3.3. *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 to 1999 was 6.0 puerulus/collector compared to 2.2 puerulus/collector from 2000 to 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

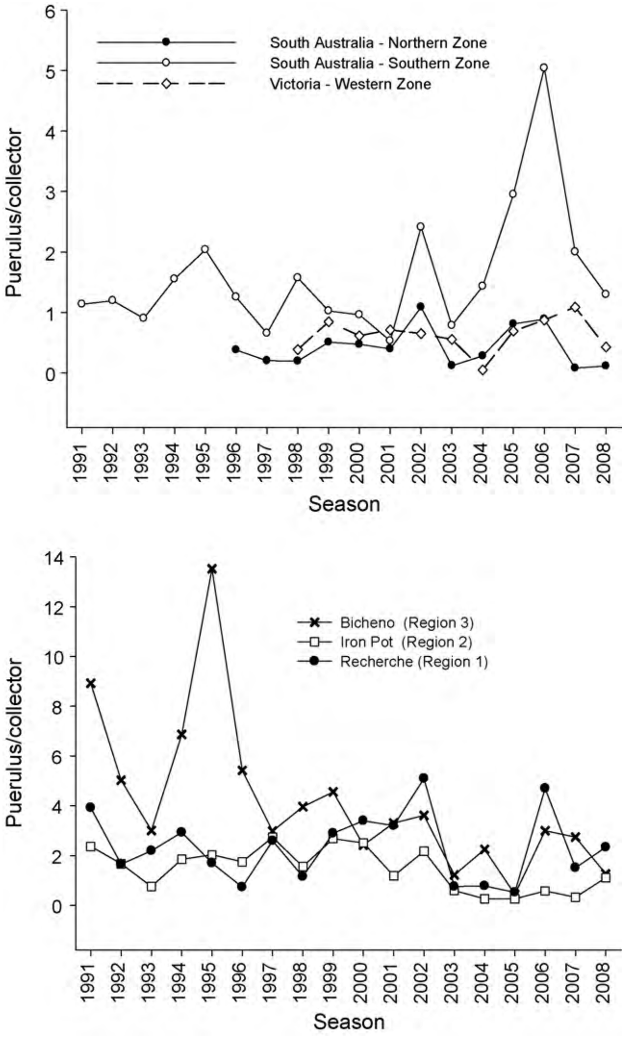

Fig. 4. Trends in puerulus settlement across South Australia, Victoria (top) and Tasmania (bottom) from 1991 to 2008.

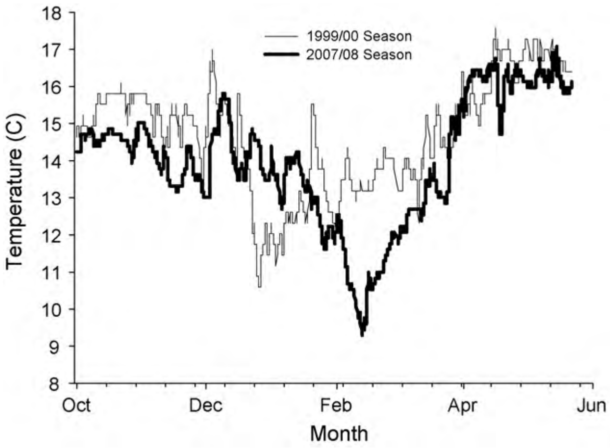

Fig. 5. Comparison of temperature profiles at the fixed monitoring site located off Southend (60 m depth) in the SZ fishery of South Australia during the 1999/2000 and 2007/2008 rock lobster seasons.

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.

3.4. Temperature data

Temperature profiles from the 1999/2000 and 2007/2008 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 2007/2008 fishing season. From mid December of 2007, temperatures fell over a two-month period from 15.6 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 2007/2008 upwelling event was significant in terms of its intensity and duration.

3.5. 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 2006/2007 to 2008/2009 was lower by ~3–4 mm CL compared to 1994/1995 and 1995/1996 estimates. Similarly, mean predicted female growth of 100 mm CL and 120 mm CL size classes were lower in 2007/2008 and 2008/2009 compared to estimates from 1994/1995 to 1996/1997. Interestingly, the lowest mean growth for males of both size classes was observed in 2007/2008, coincident with the significant upwelling event of the same season (Fig. 5).

4. 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 tonnes TACC introduced in 2003/2004 has been gradually cut to 310 tonnes for the 2009/2010 season (Fig. 7). Similarly, the southern zone TACC has been reduced from 1900 to 1400 tonnes over the same period. In Victoria, the western zone TACC has been gradually reduced from 450 tonnes in 2006/2007 to 240 tonnes for the 2009/2010 season. The eastern zone has had a marginal increase from 60 tonnes set in 2006/2007 to 66 tonnes for the 2009/2010 season. In Tasmania, the TACC has been cut from 1523 tonnes in 2008/2009 to 1323 tonnes for the 2010/2011 season. It is envisaged that further reductions will see the Tasmanian TACC gradually reduced to 1193 tonnes by 2012/2013. 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 2003/2004 season, despite the fact that catch decreased by 49% from 1001 tonnes in 1999/2000 to 503 tonnes in 2003/2004 and catch rate decreased by 47.5% from 1.43 kg/potlift to 0.75 kg/potlift, over the same period (Figs. 3 and 7; Linnane et al., 2009b). Despite

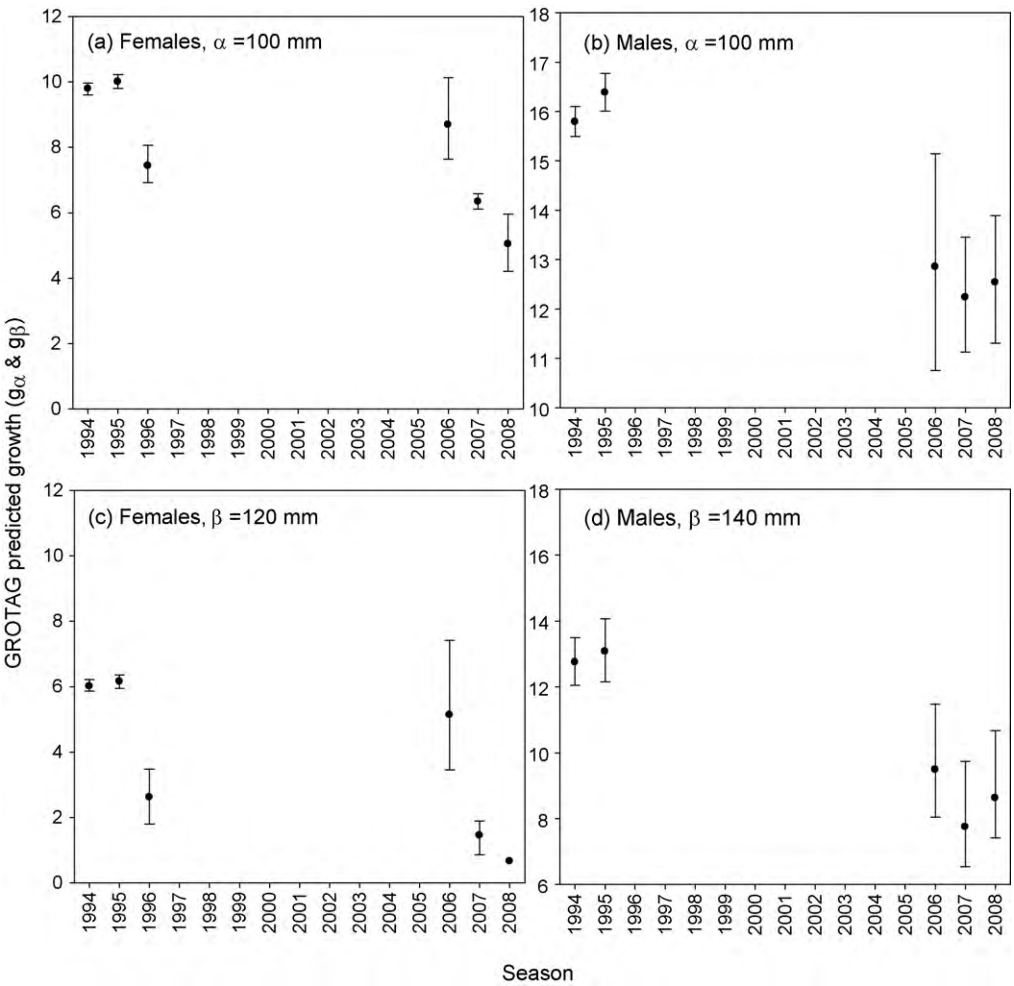

Fig. 6. Temporal comparisons of growth in both male and female lobsters in the southern zone fishery of South Australia. Data represent the season in which the lobsters were recaptured ($n = 3877$).

a TACC of 625 tonnes, only 503 tonnes were caught in 2003/2004. The TACC was subsequently reduced to 520 tonnes for 2004/2005 (446 tonnes landed) and to 470 tonnes for 2008/2009 (403 tonnes landed) with 2009/2010 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, 1980s and 1990s (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 °C) which

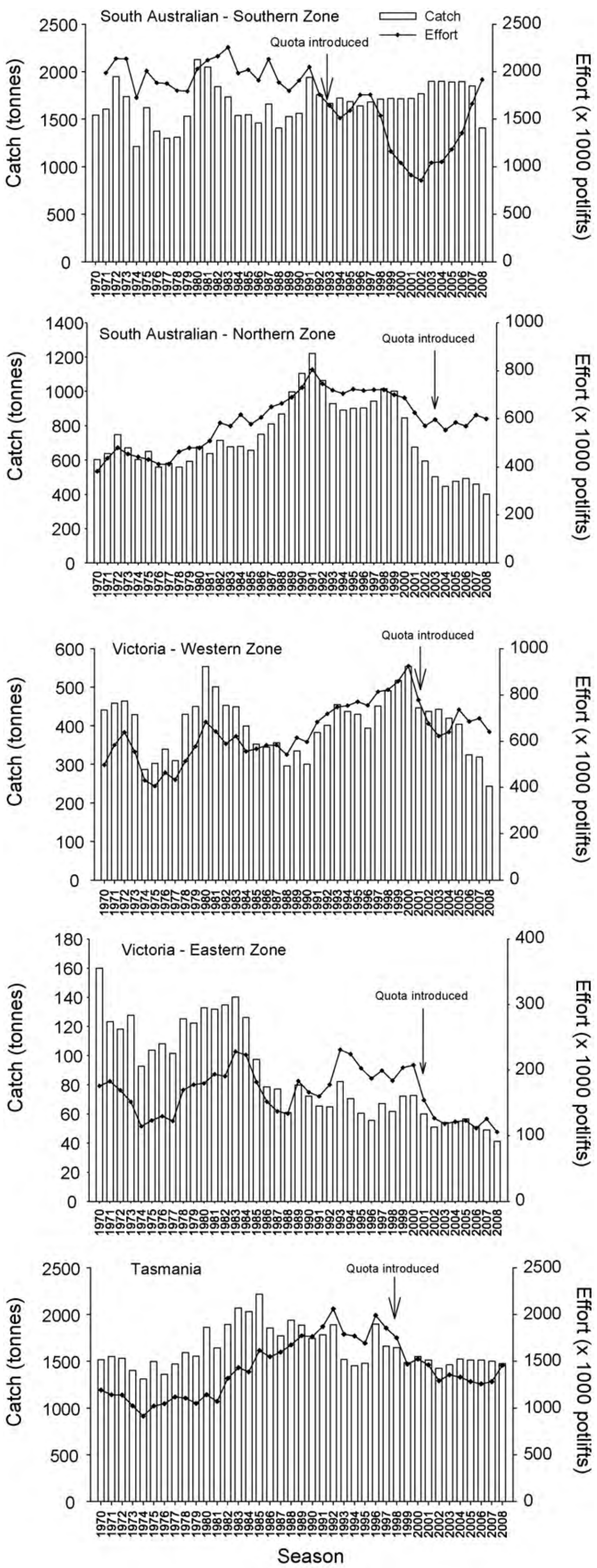

Fig. 7. Catch and effort trends across South Australia, Victoria and Tasmania from 1970 to 2008.

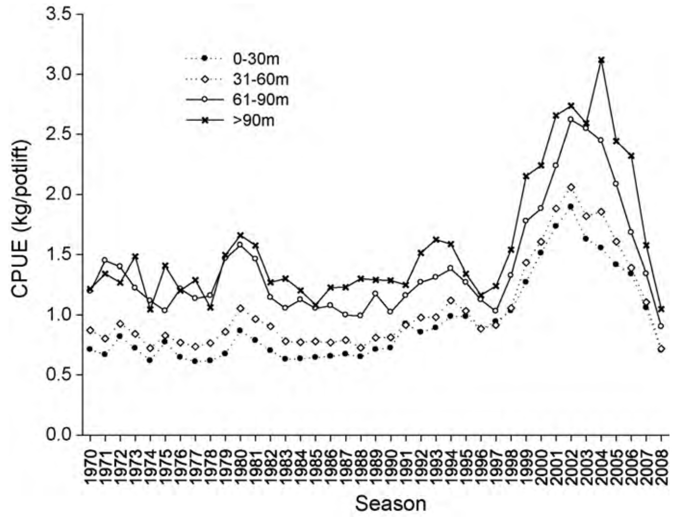

Fig. 8. Catch per unit effort (CPUE) in four depth strata in the South Australian southern zone rock lobster fishery from 1970 to 2008 (adapted from Linnane and Crosthwaite, 2009).

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; Johnston 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 juveniles 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 (Pollock et al., 1997). 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 cold-water event on all life stages of *J. edwardsii* if extreme upwelling events such as those experienced during the 2007/2008 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 2007/2008 and 2008/2009 in collector sites across Western Australia cannot be explained by environmental factors alone. 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 2010/2011 and 2011/2012 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 2007/2008 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 2600 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 ∼1300 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. 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.

Acknowledgements

We thank Kylie Davis, Peter Hawthorne, Matthew Hoare, Alan Jones, David Reilly and Ruari Colquoun for assistance provided in data entry and collation. The Fisheries Research and Development Corporation provided funds for research projects that augmented this work. We also thank licence holders in all States for the provision of commercial rock lobster fishery data.

References

Anon., 2009. National Rock Lobster Group Management 2009 Report to the New Zealand Ministry of Fisheries, http://www.fish.govt.nz.

Baelde, P., 2001. Fishers' description of changes in fishing gear and fishing practices in the Australian South East Trawl Fishery. Mar. Freshwater Res. 52, 411–417.

Bakun, A., 1990. Global climate change and intensification of coastal ocean upwelling. Science 247, 198–201.

Booth, J.D., McKenzie, A., 2009. Strong relationships between levels of puerulus settlement and recruited stock abundance in the red rock lobster (*Jasus edwardsii*) in New Zealand. Fish. Res. 95, 161–168.

Booth, J.D., Tarring, S.C., 1986. Settlement of the red rock lobster, *Jasus edwardsii*, near Gisborne, New Zealand. New Zeal. J. Mar. Fresh. 20, 291–297.

Brown, R., 2009. Western Rock Lobster Low Puerulus Settlement Risk Assessment Workshop Held 1 and 2 April 2009. Western Australian Department of Fisheries, Perth, Western Australia, http://www.rocklobsterwa.com.

Bruce, B., Griffin, D., Bradford, R., 2007. Larval transport and recruitment processes of southern rock lobster. In: FRDC and CSIRO Marine and Atmospheric Research publication Nr. 2002/2007. Australia, http://www.marine.csiro.au.

Caputi, N., 2008. Impact of the Leeuwin Current on the spatial distribution of puerulus settlement of the western rock lobster (*Panulirus cygnus*) and implications for the fishery of Western Australia. Fish. Oceanogr. 17, 147–152.

Caputi, N., Brown, R.S., Chubb, C.F., 1995. Regional prediction of the western rock lobster, *Panulirus cygnus*, commercial catch in Western Australia. Crustaceana 68, 245–256.

Chandrapavan, A., Gardner, C., Linnane, A., Hobday, D., 2009. Colour variation in the southern rock lobster *Jasus edwardsii* and its economic impact on the commercial fishery. New Zeal. J. Mar. Fresh. 43, 537–545.

Clarke, A.J., Li, J., 2004. El Nino/La Nina shelf edge flow and Australian western rock lobsters. Geophys. Res. Lett. 31, L11301.

Crear, B.J., Thomas, C.W., Hart, P.R., Carter, C.G., 2000. Growth of juvenile southern rock lobsters, *Jasus edwardsii*, is influenced by diet and temperature, whilst survival is influenced by diet and tank environment. Aquaculture 190, 169–182.

Francis, R., 1988. Maximum likelihood estimation of growth and growth variability from tagging data. New Zeal. J. Mar. Fresh. 22, 43–51.

Gardner, C., Ziegler, P., 2010. Tasmanian Rock Lobster Fishery 2008/09. Fishery Assessment Report Tasmanian Aquaculture and Fisheries Institute. University of Tasmania, 54 pp., http://www.tafi.org.au.

Gardner, C., Frusher, S., Barrett, N., Haddon, M., Buxton, C., 2006. Spatial variation in size at onset of maturity of female southern rock lobster *Jasus edwardsii* around Tasmania. Aust. Sci. Mar. 70, 423–430.

Gardner, C., Frusher, S.D., Kennedy, R.B., Cawthorn, A., 2001. Relationship between settlement of southern rock lobster pueruli, *Jasus edwardsii*, and recruitment to the fishery in Tasmania, Australia. Mar. Freshwater Res. 52, 1271–1275.

Hilborn, R., Walters, C., 1992. Quantitative Fisheries Stock Assessment: Choice, Dynamics, and Uncertainty. Chapman and Hall Inc., New York.

Hobday, D., Morison, A., 2006. Rock Lobster 2006. Report Compiled by Rock Lobster Stock Assessment Group. Fisheries Victoria Assessment Report Series No. 51.

Hobday, D.K., Ryan, T.J., 1997. Contrasting sizes at sexual maturity of southern rock lobsters (*Jasus edwardsii*) in the two Victorian fishing zones: implications for total egg production and management. Mar. Freshwater Res. 48, 1009–1014.

Johnston, D., Melville-Smith, R., Hendriks, B., Phillips, B., 2008. Growth rates and survival of western rock lobster (*Panulirus cygnus*) at two temperatures (ambient and 23 °C) and two feeding frequencies. Aquaculture 279, 77–84.

Knight, M.A., Tsolos, A., 2009. South Australian Wild Fisheries Information and Statistics Report, SARDI Aquatic Sciences Publication No. F2008/000804-1, SARDI Research Report Series No. 305, Adelaide, Australia, http://www.sardi.sa.gov.au.

Lewis, R.K., 1981. Seasonal upwelling along the south eastern coastline of South Australia. Aust. J. Mar. Freshwater Res. 32, 843–854.

Linnane, A., Crosthwaite, K., 2009. Changes in the spatial dynamics of the South Australian rock lobster fishery under a quota based system. New Zeal. J. Mar. Fresh. 43, 475–484.

Linnane, A., Dimmlich, W.F., Ward, T.M., 2005. Movement patterns of the southern rock lobster, *Jasus edwardsii*, off South Australia. New Zeal. J. Mar. Fresh. 39, 335–346.

Linnane, A., McGarvey, R., Feenstra, J., 2009a. Southern Zone Rock Lobster (*Jasus edwardsii*) Fishery 2007/08. Fisheries Assessment Report to PIRSA. South Australian Research and Development Institute (Aquatic Sciences) Publication No. F2007/000270-3, Adelaide, http://www.sardi.sa.gov.au.

Linnane, A., McGarvey, R., Feenstra, J., 2009b. Northern Zone Rock Lobster (*Jasus edwardsii*) Fishery 2007/08. Fisheries Assessment Report to PIRSA. South Australian Research and Development Institute (Aquatic Sciences) Publication No. F2007/000320-3, Adelaide, http://www.sardi.sa.gov.au.

Linnane, A., Penny, S., Ward, T., 2008. Contrasting fecundity, size at maturity and reproductive potential of southern rock lobster *Jasus edwardsii* in two South Australian fishing regions. J. Mar. Biol. Assoc. UK 88, 583–589.

McClatchie, S., Middleton, J.F., Ward, T.M., 2006. Water mass and alongshore variation in upwelling intensity in the eastern Great Australian Bight. J. Geophys. Res. 111 (C8), C08007, doi:10.1029/2004JC002699.

McGarvey, R., Feenstra, J.E., 2001. Estimating length-transition probabilities as polynomial functions of premoult length. Mar. Freshwater Res. 52, 1517–1526.

McGarvey, R., Ferguson, G.J., Prescott, J.H., 1999. Spatial variation in mean growth rates at size of southern rock lobster, *Jasus edwardsii*, in South Australian waters. Mar. Freshwater Res. 50, 333–342.

McGarvey, R., Matthews, J.M., 2001. Incorporating numbers harvested in dynamic estimation of yearly recruitment: onshore wind in interannual variation of South Australian rock lobster (Jasus edwardsii). ICES J. Mar. Sci. 58, 1092–1099.

McGarvey, R., Matthews, J.M., Prescott, J.H., 1997. Estimating lobster recruitment and exploitation rate from landings by weight and numbers, and age-specific weights. Mar. Freshwater Res. 48, 1001–1008.

McInnes, K.L., Suppiah, R., Whetton, P.H., Hennessy, K.J., Jones, R.N., 2007. Climate change in South Australia. In: Report on: Assessment of Climate Change, Impacts and Possible Adaptation Strategies Relevant to South Australia. Undertaken for the South Australian Government by the Climate Impact Group. CSIRO Atmospheric Research, http://www.csiro.au.

Pearce, A.F., Phillips, B.F., 1988. ENSO events, the Leeuwin Current, and larval recruitment of the western rock lobster. ICES J. Mar. Sci. 45, 13–21.

Pecl, G., Frusher, S., Gardner, C., Haward, M., Hobday, A., Jennings, S., Nursey-Bray, M., Punt, A., Revill, H., van Putten, I., 2009. The east coast Tasmanian rock lobster fishery—vulnerability to climate change impacts and adaptation response options. In: Report to the Department of Climate Change, Australia, www.climatechange.gov.au.

Phillips, B.F., 1986. Prediction of commercial catches of the western rock lobster *Panulirus cygnus*. Can. J. Fish. Aquat. Sci. 43, 2126–2130.

Phillips, B., 2006. Lobsters: Biology, Management. Aquaculture and Fisheries. Blackwell Publishing Ltd., Singapore.

Pollock, D.E., Cockcroft, A.C., Goosen, P.C., 1997. A note on reduced rock lobster growth rates and related environmental anomalies in the southern Benguela, 1988–1995. S. Afr. J. Mar. Sci. 18, 287–293.

Prescott, J., McGarvey, R., Ferguson, G., Lorkin, M., 1996. Population dynamics of the southern rock lobster in South Australian waters. In: Final Report to the Fisheries Research and Development Corporation 93/086 and 93/087, pp. 1–64, http://www.sardi.sa.gov.au.

Punt, A.E., Kennedy, R.B., 1997. Population modelling of Tasmanian rock lobster, *Jasus edwardsii*, resources. Mar. Freshwater Res. 48, 967–980.

Punt, A.E., Kennedy, R.B., Frusher, S.D., 1997. Estimating the size-transition matrix for Tasmanian rock lobster, *Jasus edwardsii*. Mar. Freshwater Res. 48, 981–992.

Ridgway, K.R., 2007. Long-term trend and decadal variability of the southward penetration of the East Australian Current. Geophys. Res. Lett. 34, L13613, doi:10.1029/2007GL030393.

Smith, P.J., McKoy, J.L., Machin, P.J., 1980. Genetic variation in the rock lobsters *Jasus edwardsii* and *Jasus novaehollandiae*. New Zeal. J. Mar. Fresh. 14, 55–63.