# Can production in the southern rock lobster fishery be improved?

# Linking juvenile growth, survival and density dependence to sustainable yield.

SARDI
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Department of Primary Industries

Tasmanian Aquaculture & Fisheries Institute
University of Tasmania

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Project No. 2001/070

# Can production in the southern rock lobster fishery be improved?

# Linking juvenile growth, survival and density dependence to sustainable yield.

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# NON-TECHNICAL SUMMARY

## 2001/070 Title: Can production in the southern rock lobster fishery be improved? Linking juvenile growth, survival and density dependence to sustainable yield.

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## Objectives:

1. To determine growth and mortality rates of juvenile (<80mm) lobsters throughout the range of the commercial fisheries.
2. To assess if increased juvenile density will translate to increased fishery production.
3. To evaluate techniques and obtain preliminary estimates of growth and mortality rates of puerulus / post-puerulus.

The southern rock lobster (*Jasus edwardsii*) is fished commercially across southern Australia and New Zealand. The combined catch in South Australia, Victoria and Tasmania is approximately 4,500 tonnes with a beach price of nearly 150 million dollars. Research to date in this fishery has largely focused on the late-juvenile and adult life history stages because these are readily captured with commercial fishing gear. This project aimed to investigate growth and survival from the post-settlement to late-juveniles stages, an area that has proven difficult to study because of the solitary behaviour post settlement, cryptic and inaccessible habitat and the need to sample by diving.

Sites were located in each of the three states on weather protected inshore reefs where previous surveys indicated that there would be sufficient numbers of lobsters less than 80mm CL to enable a mark and recapture study to be undertaken. Study reefs were in depths of 10m or less and surrounded by sand to reduce the movement of lobsters away from the site.

Artificial reefs were designed to overcome the difficulties of studying the early benthic stage caused by the complex, cryptic habitat in which they live. The study initially compared two substrates – Hebel (expanded concrete, CSR construction) and limestone and subsequently used Hebel as the substrate because of higher natural settlement of puerulus compared with limestone. The artificial reefs (2.40m x 1.20m x 0.21m) were constructed by layering Hebel blocks above and below a layer of concrete 7cm thick. A steel frame was attached both above and below to provide support, and four smaller blocks are attached to the top frame. The whole reef was then attached to four concrete-filled tyres located at the corners of the reef, which act to anchor the reef securely to the sea floor. Three hole sizes (12, 16 and 25mm diameter) and two crevice sizes (25 and 60mm high) were provided in the blocks. The holes were preferred to the crevices with medium holes (16mm) occupied by significantly more pueruli. No pueruli were found in the large crevices indicating that puerulus prefer a solitary single habitat slightly larger than their body size. The results demonstrated that artificial reefs made of Hebel are suitable man-made structures that can be used to study juvenile lobsters that are normally inaccessible. Careful design of these structures is warranted if the design is to maximise habitat. With the increased global interest in the use of artificial reefs to study fish behaviour, enhance fish stocks and provide sanctuaries, these results are the first to attempt to mimic lobster habitat in Australia. They offer considerable potential to understand the behaviour and dynamics of an important life history phase of rock lobster that is considered the most vulnerable of the benthic life history phase.

The condition of juvenile lobsters was measured as an indicator of growth and used to explore growth differences between the three sample sites in Tasmania. Of particular interest was the comparison of condition when density had been increased. Haemolymph samples were taken from juvenile lobsters along with the third pleopod to assess the moult stage as moult stage and haemolymph colour are highly correlated. The haemolymph protein colour was measured with a hand-held refractometer. No effect of size or sex was found on the condition of juvenile lobsters. The results indicated that condition was highest at the Point Leuseur site and lowest at the density-enhanced site at Pigeon Holes. Point Leuseur was significantly different from Pigeon Holes and Glenvar Bay, which may reflect the higher growth rate. Although the enhanced Pigeon Holes site was not significantly different from the adjacent Glenvar Bay site, the lower mean condition index of the Pigeon Holes site suggests that condition may have been impacted on by the addition of lobsters. Over 1,000 lobsters were added to the Pigeon Holes site to enhance the site. While this was equivalent to approximately 70% of the lobsters captured at this site, it was estimated that the density was only increased by about 15%.

The settlement habitat of the early post settlement stages of southern rock lobsters is very complex, so that recapturing tagged juveniles to assess growth is virtually impossible. This study used six artificial reefs in Tasmania and one in Victoria to provide habitat for puerulus tagged with microwire coded tags. A total of 729 puerulus were tagged in Tasmania and 79 were recaptured with time at large ranging from 35 to 355 days. In Victoria, 90 puerulus were released onto the reef with 7 recaptures. No difference in growth rate between males and females was found. Growth rates were greater for pueruli tagged and recaptured in summer than those recaptured after exposure to combined summer and winter temperatures. Puerulus grew from settlement size of around 11 mm CL to juveniles of approximately 35 – 51 mm CL after twelve months. The majority of the variability in growth could be explained by average water temperature for animals that had been at large over a summer and winter. Examination of the timing of settlement in Tasmania showed that the two settlement peaks in winter and spring would provide a single cohort after one year due to the lower winter growth.

Growth of juveniles was estimated from tag recapture data from each State. Differences in annual growth rates were evident between the sexes at 50 mm CL with males growing 1.4 times faster than females. Individual growth increments were similar between the sexes, and the higher growth of males resulted from a higher moult frequency. A significant reduction of moult frequency was found in females as they reached sexual maturity. No significant difference was found in growth rates between the States when all sites within each State were combined. The only difference in growth rate found between sites was the significantly higher growth rate at Point Leuseur compared to Livingstons. Density manipulations did not result in any significant changes to growth.

The survival of pueruli was examined at two sites, Bicheno (two artificial reefs) and Derwent Estuary (four artificial reefs). Puerulus and early benthic phase juveniles were captured on artificial collectors, individually marked with microwire tags, and released onto artificial reefs to estimate survival through the first year post-settlement. At the Bicheno site, the artificial reefs were in close contact with natural reef, while at the Derwent Estuary site the artificial reefs were located on sand and some distance from natural reef. Despite these differences, artificial reefs at both locations were rapidly colonised by a range of reef animals including potential predators of juveniles such as larger lobsters and fish. Releases occurred on 16 occasions over a 24-month period and seven recapture surveys were conducted quarterly. No recaptures of tagged lobsters were recorded from a total of 229 releases at the Bicheno site, effectively giving an estimated survival of zero. Untagged juveniles were recovered from this site but all were small and apparently recently settled. In contrast, 79 tagged juveniles were recovered from the Derwent Estuary site from a total of 500 releases. A Brownie-type mark-recapture model was used to estimate survival from this data because of the need to account for removals; removals occurred through the course of sampling as juveniles were sacrificed to remove the tag and record the unique code. Apparent annual survival from the Derwent Estuary data was estimated at 0.23±0.08. The apparently low survival at Bicheno is in agreement with the observed low abundance of juveniles in this area despite consistently high puerulus catches on collectors at an adjacent long-term monitoring site. Likewise, puerulus catches at the Derwent Estuary puerulus monitoring site are typically low yet the area has high abundance of juveniles, which can be explained by the high survival observed in this study through the first year. An annual survival estimate of 23% is thus likely to be towards the upper limit of the range of actual survival of early benthic phase juveniles around the Tasmanian coast.

Apparent survival (inclusive of mortality and loss through emigration) was quantified for juvenile southern rock lobsters with a mark-recapture survey on reefs in Tasmania and South Australia. A total of 6530 juveniles were captured by hand by divers and released at four sites (Glenvar Bay, Point Leuseur, Pigeon Holes and Livingstons). Density of lobsters at the Pigeon Holes site was manipulated by the addition of 1021 juveniles. Annualised survival estimates from most sites ranged from 5 to 15% for smaller animals less than 45 mm CL. Highest survival of smaller juveniles was at the Pigeon Holes site in the Derwent Estuary where very high survival was also recorded for early benthic juveniles. There was some evidence of declining apparent survival with increasing density at the Pigeon Holes site relative to the adjacent Glenvar Bay site. Further evidence for a density dependent effect was the decline in apparent survival with increasing lobster size. This pattern may have been due to both movement and mortality, but retention for larger animals at these reefs was clearly less than for smaller lobsters. The effect of size on rates of survival at both Point Leuseur and Glenvar Bay appeared to occur in a discontinuous manner with a shift at around 65 mm CL and may represent shelter limitation for dens suitable for co-habitation. The lack of larger lobsters at the Point Leuseur and Pigeon Holes sites were in sharp contrast to the Maria Island Marine Reserve and Crayfish Point Scientific Reserve, which are in adjacent regions and support large numbers of large lobsters. These results indicate the complexities of inshore reefs and the substantial differences in retention rate of larger lobsters. Although it was not possible in this study to separate emigration from mortality, the rapid decline in apparent survival would suggest that emigration was a major component of the low survival estimate. If this is the case, then some inshore reefs act as ‘feeder reefs’ for other regions of the fishery. Identification of feeder or nursery reefs has implications for management of inshore reefs and marine protected areas as these reefs would have greater impact than predicted from their physical area.

The size frequency and movement patterns of juvenile lobsters tagged and released at the Pigeon Holes and Glenvar Bay sites in Tasmania and the Livingstons site in South Australia were investigated. Specifically, the initial size of all releases was compared to the initial size of all recaptures across a range of size classes from 30 to 115 mm CL. At Pigeon Holes and Livingstons there were fewer lobsters recaptured in the large size range compared to the smaller size range supporting the survival conclusion that these reefs do not support larger sized lobsters. Glenvar Bay had the opposite trend for females and all sites had greater recapture rates for larger females suggesting that males preferentially move off the reefs. Movement rates within sites were low with most lobsters being found in the vicinity of where they were tagged. Commercial and recreational fishers also reported several recaptures. Due to the growth rates these recapture would be limited to the larger size ranges that were tagged at the start of the project. Recaptures have occurred up to 7 km from the site of tagging.

Seasonal patterns and annual patterns of puerulus settlement across South Australia, Tasmania and Victoria were determined along with appropriate time lags between puerulus settlement and model-estimated recruitment. A strong seasonal pattern in settlement was observed across all three states. Winter settlement was the most prominent, with puerulus counts in all sites increasing in June and peaking in August. Annual indices in settlement over the period 1994 to 2003 were also comparable

across States with settlement trends in South Australia and Victoria closely correlated. These results suggest factors affecting recruitment are widespread and point towards common oceanographic and/or environmental influences. Overlap periods between model recruitment estimates and puerulus settlement indices varied from 7 to 11 years depending on the time each State implemented their puerulus monitoring programs. In northern regions of the fishery (Victoria, Northeastern Tasmania and South Australia), recruitment was relatively fast, with an average period of 4 years between settlement and recruitment to the fishery. In regions further south, the time between settlement and recruitment increased to 5 years at eastern Tasmania and 8 years at southeastern Tasmania. This increase in time lag is expected due to the decline in average water temperatures (and therefore slower growth rates) with increasing latitude. Within each region there is at least one period where the match between settlement and recruitment fails; the cause for this is uncertain and will need a longer time series of data before processes can be linked to these patterns. For the majority of data points there is a strong positive correlation indicating the potential for puerulus settlement indices to be used for future management of the resource.

## OUTCOMES ACHIEVED

This study developed an artificial reef structure, which enabled studies of growth and survival of juvenile lobsters in their first year after settlement to be undertaken. This technology will be applicable to future studies of the early life history of the benthic stages of the southern rock lobster. Ecological studies of temperate reef communities, which are currently hindered by the complexity of the reef system, could also benefit from the use of artificial reefs.

Knowledge of the complex early juvenile phase of lobsters has been increased substantially through this project. Significant advances include the first estimates of survival and growth rate for newly settled and juvenile lobsters. In addition, the study identified reefs that appear to act as nursery reefs that supply juveniles to adjacent regions has not been previously documented for the first time in this species.

Links established between puerulus settlement and recruitment justify the incorporation of puerulus settlement indices into assessment models for both predicting future catches and as indicators of longer term trends in recruitment.

### Keywords:

Southern rock lobster, post settlement, juvenile, growth, survival

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# FINAL REPORT

## 2001/070 Can production in the southern rock lobster fishery be improved? Linking juvenile growth, survival and density dependence to sustainable yield.

# Background

The southern rock lobster (*Jasus edwardsii*) hereafter referred to as lobster, is an important resource in South Australia, Victoria and Tasmania. The combined catch is approximately 4,500 tonnes with a beach price of nearly 150 million dollars. Over 650 fishers operate mainly out of rural coastal towns and the Industry makes an important contribution to the socio-economic fabric of these areas. Lobsters are also caught recreationally by diving and potting (except in Victoria) with over 20,000 recreational licenses issued annually in southern Australia.

Management systems (input and output controls) vary between, and even within States. All states use or are about to introduce models with forward projecting capabilities. Growth and mortality of puerulus and juvenile stages have not been studied to date and therefore are not included in the models. This work will aim to provide these inputs.

Nearly a decade ago Tasmania, South Australia and Victoria began puerulus settlement monitoring as a first step towards a better understanding of lobster recruitment dynamics. These projects are now starting to provide an ability to predict catch rates several years in advance. To incorporate this information into stock assessment models in each state, information on growth and mortality is required. It is expected that linking settlement indices to future commercial catches will have a profound impact on the management and marketing of lobsters, similar to that demonstrated for the western rock lobster in WA.

Recent studies have indicated that a decline in juvenile abundances has occurred in northern regions of Tasmania during the last 40 years. Through manipulation experiments, this work will determine if increased juvenile abundance translates to increased production. Declines in egg production have corresponded with substantial reductions in the spawning stock as the fisheries for southern rock lobster developed. Anecdotal evidence from divers and fishers support this.

Recognising the need for a greater insight into post settlement processes the FRDC organised an international workshop on the subject in 1999 entitled "Workshop on post settlement processes in southern rock lobster". This workshop brought together International experts from USA, NZ and Japan. The outcomes of the workshop are detailed in FRDC Final Report No. 1998/362. Participants at the workshop recognised that to answer most of the questions on post-settlement processes would take a large team and even larger period of time.

However, three crucial issues were identified:

a) Prediction of future catches from puerulus/juvenile abundances,

b) Prediction of the value which greater natural larval recruitment, re-seeding, or enhancement would have on the resource, and

c) Prediction of the effects which puerulus removal (for aquaculture) would have on recruitment to the fishery.

To address these issues, five areas of research were identified:

1) Identify critical/preferred habitat, for pueruli, post-pueruli and juveniles

2) Estimate growth rates of 0+ juvenile to pre-recruit lobsters,

3) Estimate mortality rates of 0+ juvenile to pre-recruit lobsters,
4) Determine patterns of shelter use and movement, and
5) Document principal predators and competitors.

This project is a core outcome of this workshop and will specifically address areas 2 and 3 and will provide valuable data on areas 1, 4 and 5.

# Need

Across all southern states there is a strategic need for research to improve assessment of the stocks, improve advice on management alternatives, and provide forecasts with reduced uncertainty of future stock size and, by implication, potential catches. This project addresses this need.

In all states, current management objectives include rebuilding of the stocks. Current legal sized biomass is principally based on recent recruits to the fishery. As stocks rebuild, the biomass will contain a greater proportion of lobsters that had recruited prior to the last season. As these lobsters will have increased in size since recruiting, the average weight of the legal sized biomass will have increased. Thus bigger stocks will certainly provide greater yields from each recruit and therefore lead to greater productivity. As the number of eggs that a female lobster broods is a cubic relationship to her size, a small increase in size will lead to a much larger increase in the number of eggs produced. Thus large gains may also be possible through the feedback from greater egg production from the rebuilding legal sized biomass. The potential for more eggs to lead to higher recruitment to the fishery will in part be dependent on events occurring during the planktonic stage and in part on rates of growth and mortality of the pre-recruit benthic stages. Therefore there is a need to acquire this information to enable managers to take egg production into account when setting management measures.

Tasmania was about to start a puerulus harvesting program as part of an attempt to establish a rock lobster aquaculture industry in the state. Part of this activity was a return of a proportion of the animals to the wild after a period in culture, estimated to be equal or in excess of those that would have survived over a similar period in the wild. This aimed to ensure neutrality of puerulus harvest. The proportion returned was based on initial poorly supported estimates of mortality during the first year of benthic life. The results of this study therefore had a significant application for this related work.

The high value of rock lobster fisheries in southern Australia means that even small increases in the catch may have substantial benefits. A 5% improvement in catch might result in a $10 million increase in landed value with flow on benefits to southeastern Australian rural coastal communities. Concern has been voiced that increases in production may be offset by lower prices due to supply outstripping demand. However, price increases during the past decade suggest that demand is growing more rapidly than supply. Economic analyses of the fishery conducted in the early 1990s also showed that rock lobsters had characteristics of a supply-price elastic product, with local price largely unaffected by long-term changes in supply due to significant international competition. It therefore seems reasonable to conclude that higher production (without increased effort) in southern Australia will have a positive impact on the economy.

# Objectives

1. To determine growth and mortality rates of juvenile (<80mm) lobsters throughout the range of the commercial fisheries.
2. To assess if increased juvenile density will translate to increased fishery production.
3. To evaluate techniques and obtain preliminary estimates of growth and mortality rates of puerulus / post-puerulus.

# Chapter 1 - Sampling methods and site descriptions

## Sampling methods

Lobsters were captured by SCUBA divers using snares, wires or gloved hand, or a combination of these and transferred to a mesh catch bag where they were held until the completion of the dive or until sufficient numbers had been collected. Lobsters were then returned to the boat, where they were individually tagged using Hallprint® mini T bar tags. Each tag was identified by a unique number, and were colour coded yellow for Tasmania, blue for South Australia and green for Victoria. All tags were inserted ventrally, using a Dennison tag-fast® III tag applicator, into the anterior oblique muscle between the first and second abdominal sterna. Data recorded upon initial tagging and subsequent recapture, included location (GPS coordinates), sex, CL, depth, sexual maturity based on setal development and damage, including loss of legs or antennae and scars caused by tag shedding. A plastic cable tie, placed around the base of an antenna on each lobster, provided an aid to identification and meant that unnecessary handling of lobsters tagged the previous day could be avoided. During the entire process, lobsters were kept cool and out of direct sunlight as much as possible to reduce stress. Once measurements were completed, lobsters were released onto the reef site. Initially, this involved divers swimming bags of lobsters down to the reef and placing individuals into likely looking dens. Despite these efforts, observations showed lobsters were highly mobile following release and preferred to find their own dens. From then on, lobsters were gently ‘poured’ out of the catch bags onto reef and allowed to find their own refuge.

## Site characteristics and selection criteria

Sites were selected in each of the three states based on a number of key criteria. Firstly, they needed to be located on inshore reefs with water depths of 10m or less to afford divers sufficient bottom times to conduct the survey. Secondly, they had to provide adequate protection from prevailing winds and swell and be readily accessible to small boats. Much of the Victorian and South Australian coastline is susceptible to southerly swell and this greatly reduced the availability of suitable study sites. Thirdly, where possible, sites were chosen that had reef surrounded by sand to reduce the movement of lobsters from the study site. Finally, the sites had to possess sufficient numbers of lobsters less than 80mm CL to enable a mark and recapture study to be undertaken.

A total of six study sites were chosen, with three sites in Tasmania, two in South Australia and one site in Victoria (Table 1).

**Table 1. Summary of the key habitat features of each site**

| Site | Reef type | Floral assemblages | Depth | ‘Catchability’ |
|---|---|---|---|---|
| **Glenvar Bay (Tas)** | Flat-lying, arenite/lutite boulders topped with rubble | *Ecklonia radiata* & red algae | 5-9 m | Moderate-high |
| **Pigeon Holes (Tas)** | Medium profile, arenite/lutite | *Ecklonia radiata* & red algae | 0-8 m | Moderate |
| **Pt Leuseur (Tas)** | Medium profile, dolerite reef with vertical cracks and larger boulders | *Ecklonia radiata* & *Phyllospora comosa* | 4-10 m | High |
| **Gerloffs (SA)** | Medium-high profile, limestone with some deep ledges | *Cystophora/Sargassum &, Caulerpa* | 5 m | Low-moderate |
| **Livingstons (SA)** | Low profile, limestone platforms, shallow ledges | *Cystophora/Sargassum, Caulerpa & Posidonia/ Amphibolis* | 2-5 m | Moderate |
| **Port Campbell (Vic)** | Medium-high profile,limestone, deep ledges & complex boulder reef | *Cystophora & Caulerpa* | 2-7 m | Low |

## Tasmania

Two adjacent study sites were selected at Pigeon Holes (Lat. 43° 00.565' S  Lon. 147° 23.842' E) and Glenvar Bay (Lat. 43° 00.211' S  Lon. 147° 23.797' E), in the Derwent River, and a third site was selected at Pt Leuseur (Lat 42° 39.567' S  Lon.148° 00.417' E) near Maria Island on the east coast (Figure 1).  An increased density trial was conducted at Pigeon Holes and unaltered density trials were conducted at the other two sites.

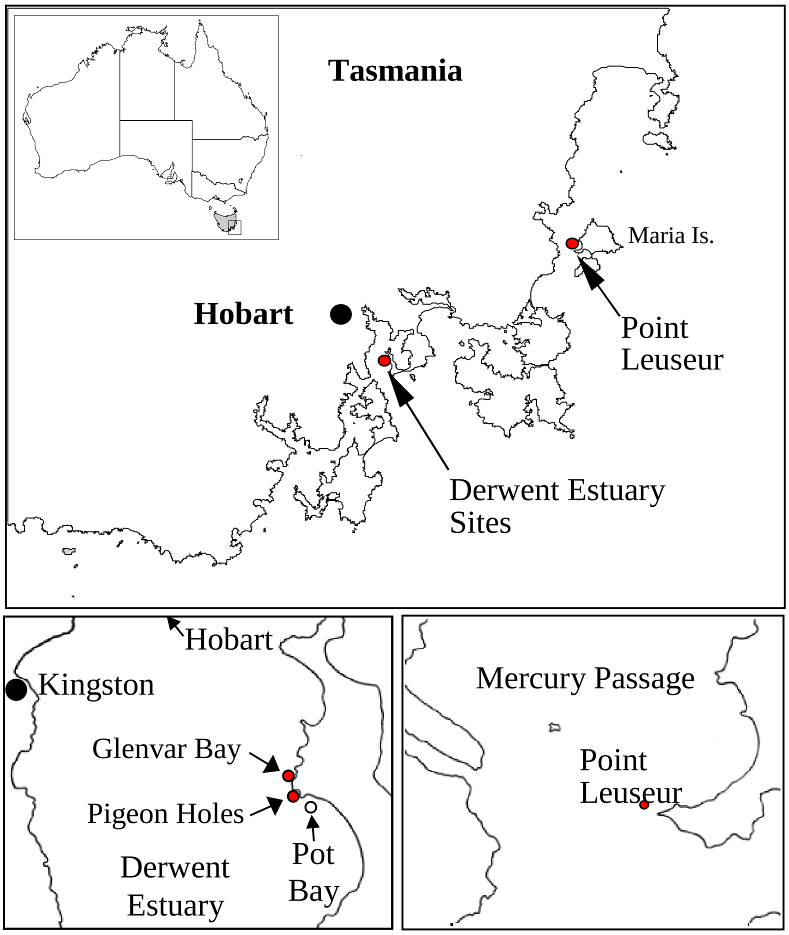

**Figure 1.** **Location of Tasmanian sites – Pigeon Holes, Glenvar Bay, Pot Bay (lower left panel) and Pt Leuseur (lower right panel).**

### Glenvar Bay

Glenvar Bay has a flat-lying reef, predominantly arenite/lutite sequences with dolerite intrusions, topped with a complex pile of rubble. It supports an algal community dominated by *E. radiata*, but also includes fine red algal species. This reef is in 5-9m of water and is bordered by sand on three sides, the fourth side being the shoreline (Figure 2).

### Pigeon Holes

The reef at Pigeon Holes is of similar mineral composition to that at Glenvar Bay, however, there is more medium profile reef at Pigeon Holes and less patchy reef.  The reef starts at the foot off a cliff and extends to a depth of 8m where it is bordered by sand (Figure 3).  To the east the reef extends to a low headland and rock platform, ending in a sandy beach.  To the west a narrow strip of reef joins this site with Glenvar Bay, approximately 500 m distant.

**Point Leuseur**

The site at Point Leuseur consisted of an isolated body of reef, roughly circular in shape and approximately 100m in diameter. The reef was surrounded by sand, providing a natural barrier to lobster movement, and ranged from approximately 4 to 10 m in depth (Figure 4). The site was located in the Mercury Passage, a body of water approximately 20km long and 10 km wide that separates Maria Island from the east coast of Tasmania (Figure 1). The island offered a degree of protection from oceanic swells, enabling diving on all but a few occasions. Tides at times were strong in this area (1 knot +) and the environment was typically marine. The reef supported a complex algal community consisting primarily of *Ecklonia radiata* and *Phyllospora comosa* along with a diverse range of encrusting corallinaceae and turfing red algae. The reef also supports dense stands of *Undaria pinnatifida* during its growing season.

The reef is a mixture of dolerite (mostly Jurassic age) and Cretaceous syenite masses (Land Information System Tasmania), which results in a reef with high structural complexity and medium rugosity. Other species noted on this reef include a wide variety of wrasse, leatherjackets and other reef associated fish, as well as a large range of invertebrates, notably large numbers of *Heliocidaris erythrogramma*.

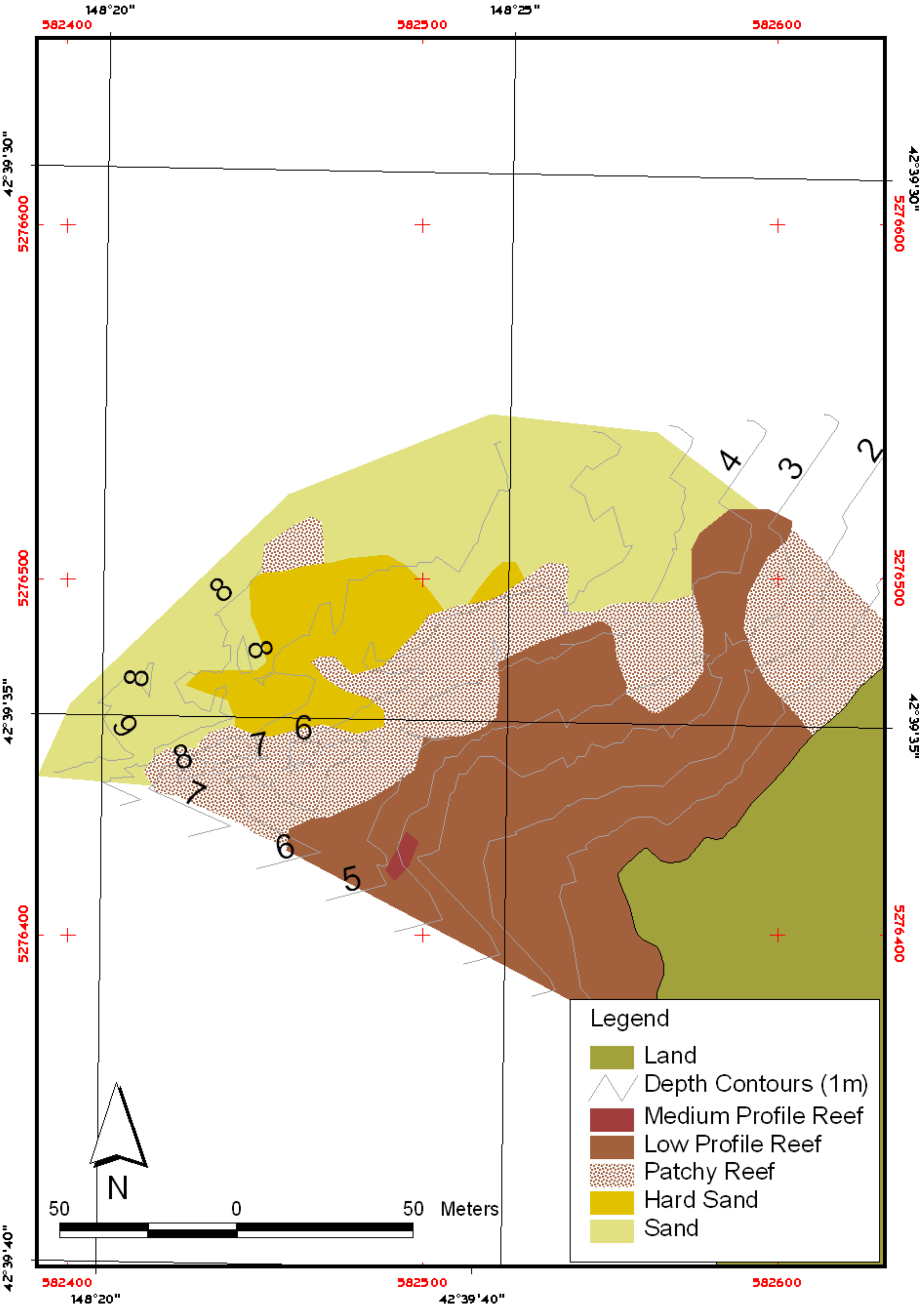

Figure 2. Map of reef type at the study site in Glenvar Bay (Tas).

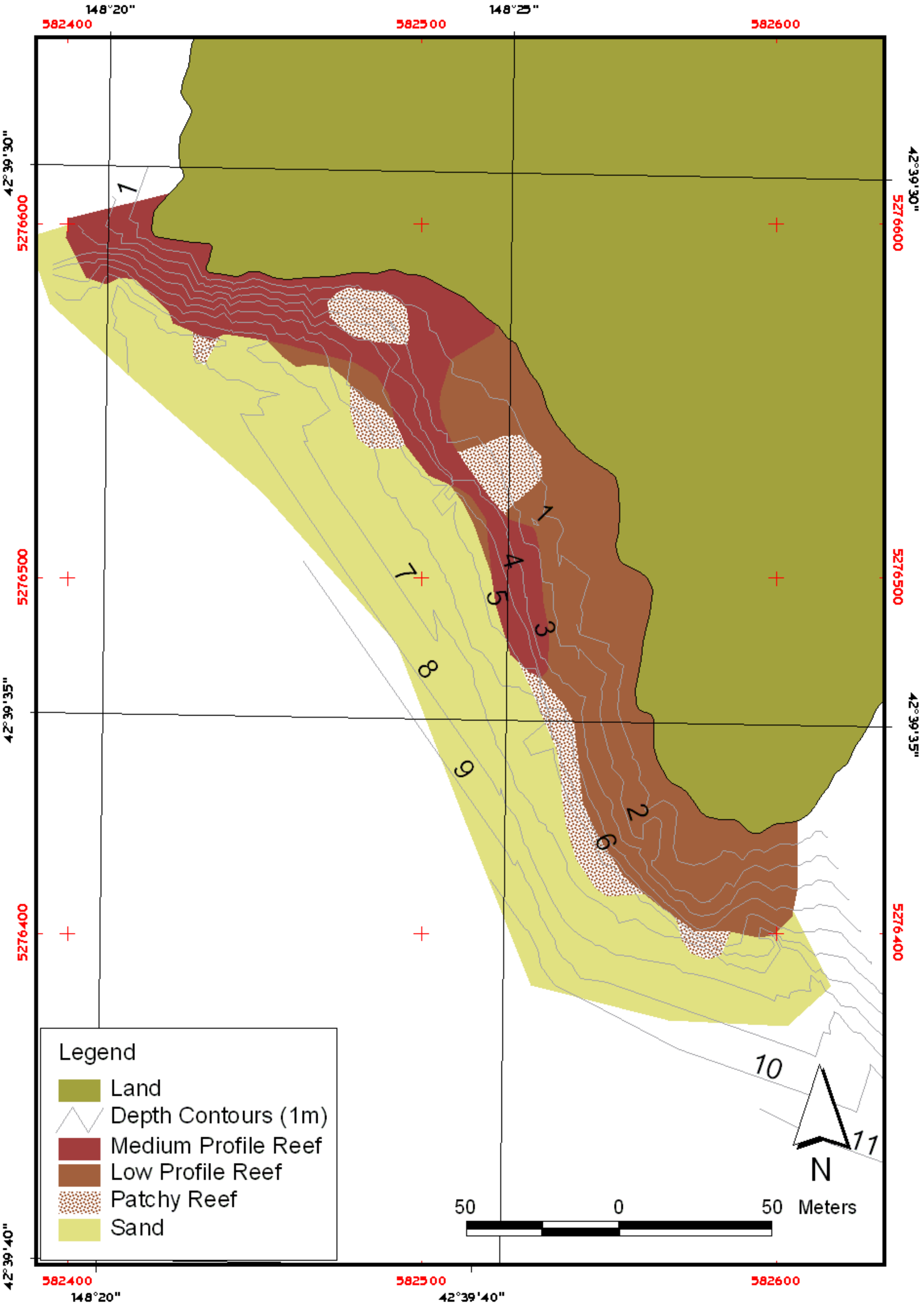

Figure 3. Map of reef type at the Pigeon Holes study site (Tas).

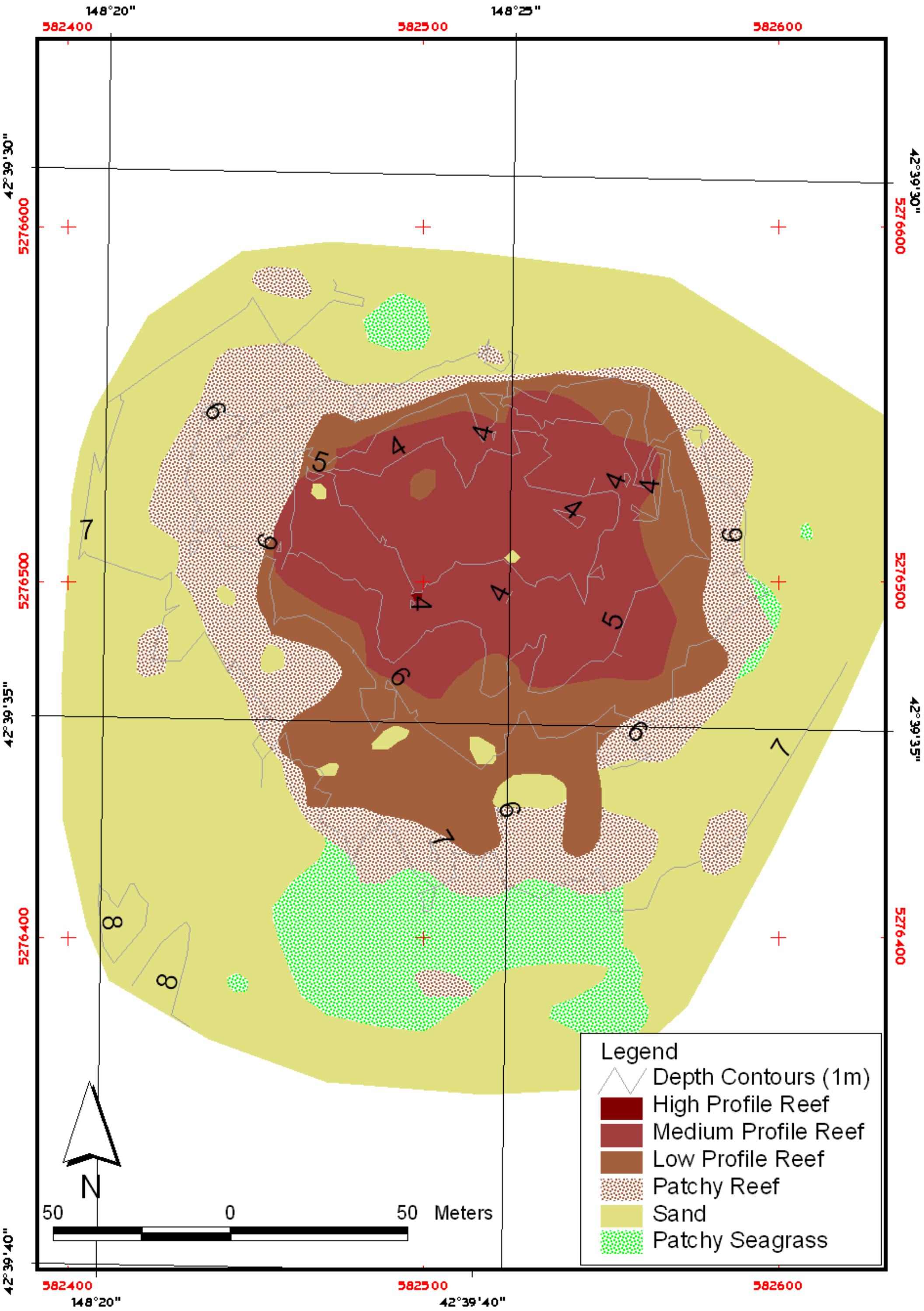

Figure 4. Map of reef type at the Pt Leuseur study site (Tas).

## South Australia

The South Australian sites were in Gerloffs Bay and Livingstons Bay, two adjacent bays, located between Carpenter Rocks and Blackfellow Caves (Figure 5). The position of survey sites within these bays are positions of seven survey sites within these bays are shown in Table 2. This stretch of coast is made up of a series of small bays with sandy beaches, between low, rocky headlands. The bays are typically shallow and protected from southerly swells, to some degree, by an outer reef approximately 1000m from shore. This together with the abundance of juvenile lobsters made this area an attractive study location.

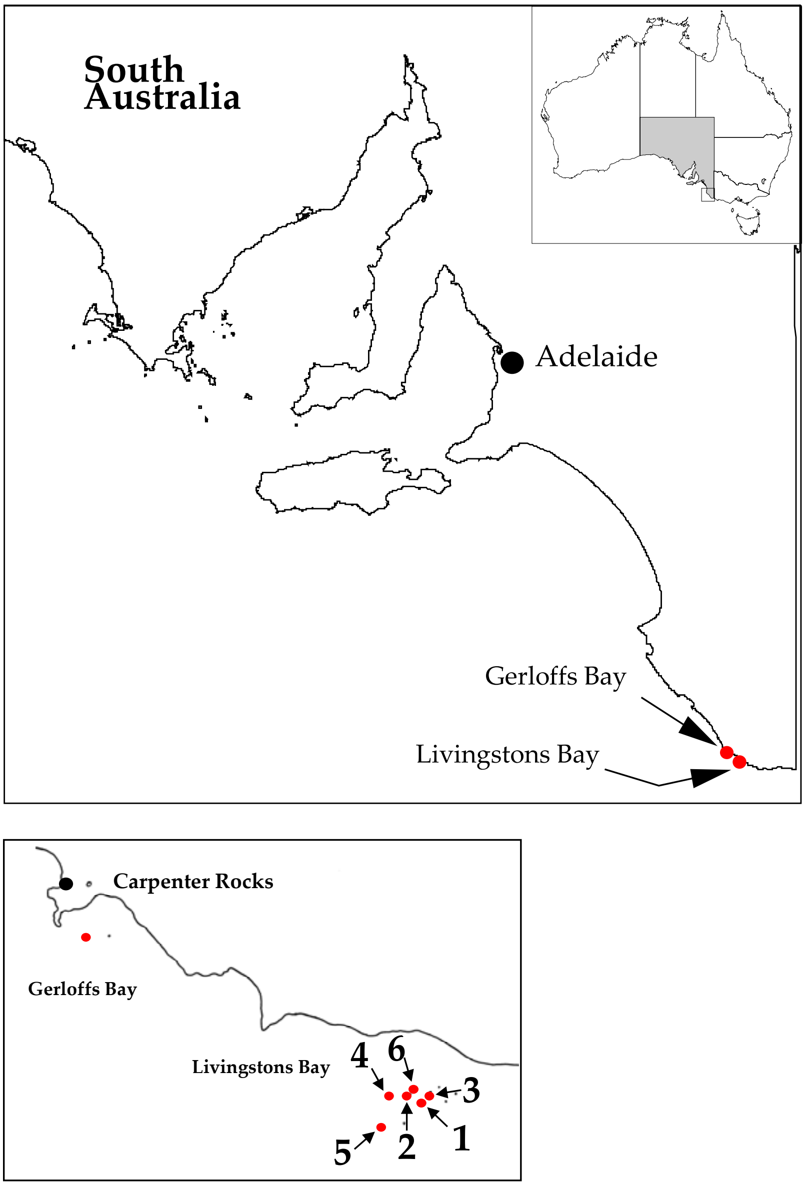

**Figure 5.** **Location of the sites in South Australia. The numbers in Livingstons Bay in the lower panel indicate the individual sites Livingstons 1 – 6.**

Table 2. Position of sites within Geloffs Bay and Livingstons Bay

| Site | Latitude | Longitude |
|---|---|---|
| **Gerloffs Bay** | 37° 55.224' S | 140° 24.186' E |
| **Livingstons Bay – Site 1** | 37° 56.330' S | 140° 26.633' E |
| **Livingstons Bay – Site 2** | 37° 56.267' S | 140° 26.522' E |
| **Livingstons Bay – Site 3** | 37° 56.285' S | 140° 26.708' E |
| **Livingstons Bay – Site 4** | 37° 56.274' S | 140° 26.373' E |
| **Livingstons Bay – Site 5** | 37° 56.447' S | 140° 26.315' E |
| **Livingstons Bay – Site 6** | 37° 56.242' S | 140° 26.588' E |

### Livingstons Bay

Known locally as Livingstons, this bay was between 2-5 m in depth, with a seabed consisting of limestone, interspersed with sand. Low profile, platform reef predominated the area, with patchy reef occurring in the shallower, onshore sections (Figure 6). Although widespread throughout the bay, most reef provided limited lobster habitat due to its lack of relief. In a number of locations, however, erosion of the seabed had led to the formation of mushroom shaped, rock platforms standing between 0.5-2 m above the bottom, with shallow ledges providing prime lobster habitat and allowing relatively easy collection of lobsters by divers. Five of these rock platforms were selected for the study on the first field trip in June 2002 and a sixth was selected inshore of the others on the second trip in October 2002 (Figure 5 and Figure 6). Sites were positioned in a rough cross pattern in order to detect lobster movement within the bay. Sites ranged from 400 m to 1000 m from shore and were between 150 – 400 m apart.

The area surveyed (SARDI Aquatic Sciences) was largely dominated by both brown algae and mixed brown and green algae (Figure 7). Seagrass was only found in a small area close to shore. The brown algal assemblage was largely comprised of brown branching macroalgae such as *Cystophora* and *Sargassum*, the mixed brown and green assemblage was comprised mainly of *Cystophora*/*Sargassum* and *Caulerpa* species. Mixed seagrass and algal assemblages were areas in which either *Posidonia* or *Amphibolis* and *Cystophora* were found in almost equal proportions. Mixed algal assemblages were comprised largely of a mixture of red foliaceous algae and *Cystophora* or *Sargassum*. The algal assemblages occurred predominantly on low profile platform reef, whereas the seagrass assemblages were in an area of patchy reef (Figure 7).

### Gerloffs Bay

This Bay is situated approximately 5 km NW of Livingstons and was chosen as the site of the density manipulation component of the experiment (Figure 5). The site (Lat. 37° 55.224' S Lon. 140° 24.186' E) had a maximum depth of 5m and a similar algal assemblage to that encountered at Livingstons. The limestone reef was generally higher in profile than at Livingstons and many ledges were deeper, making recapture more difficult. Lobsters were translocated to this site from Livingstons to increase the density.

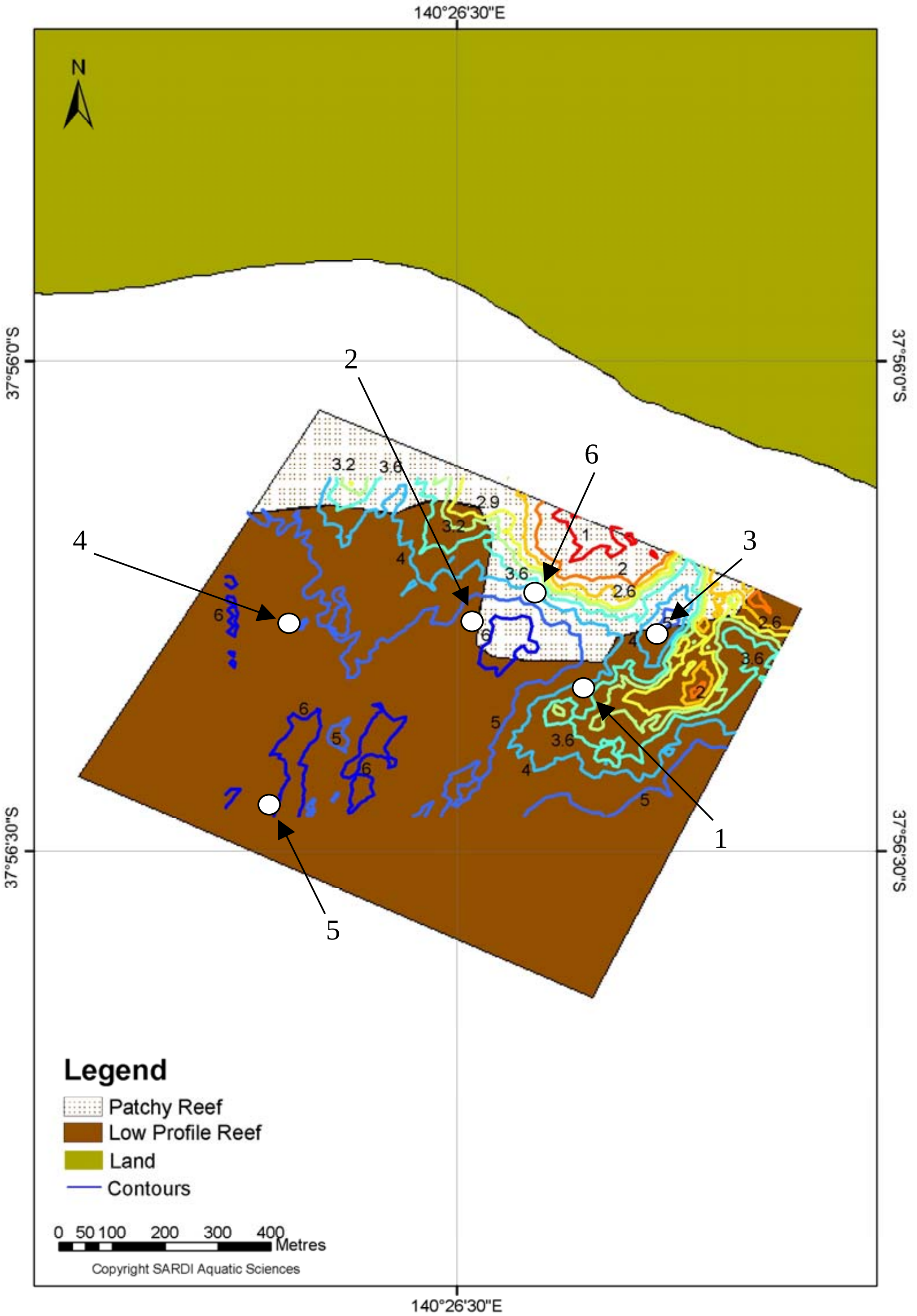

**Figure 6.** Map of reef type in study area in Livingstons Bay

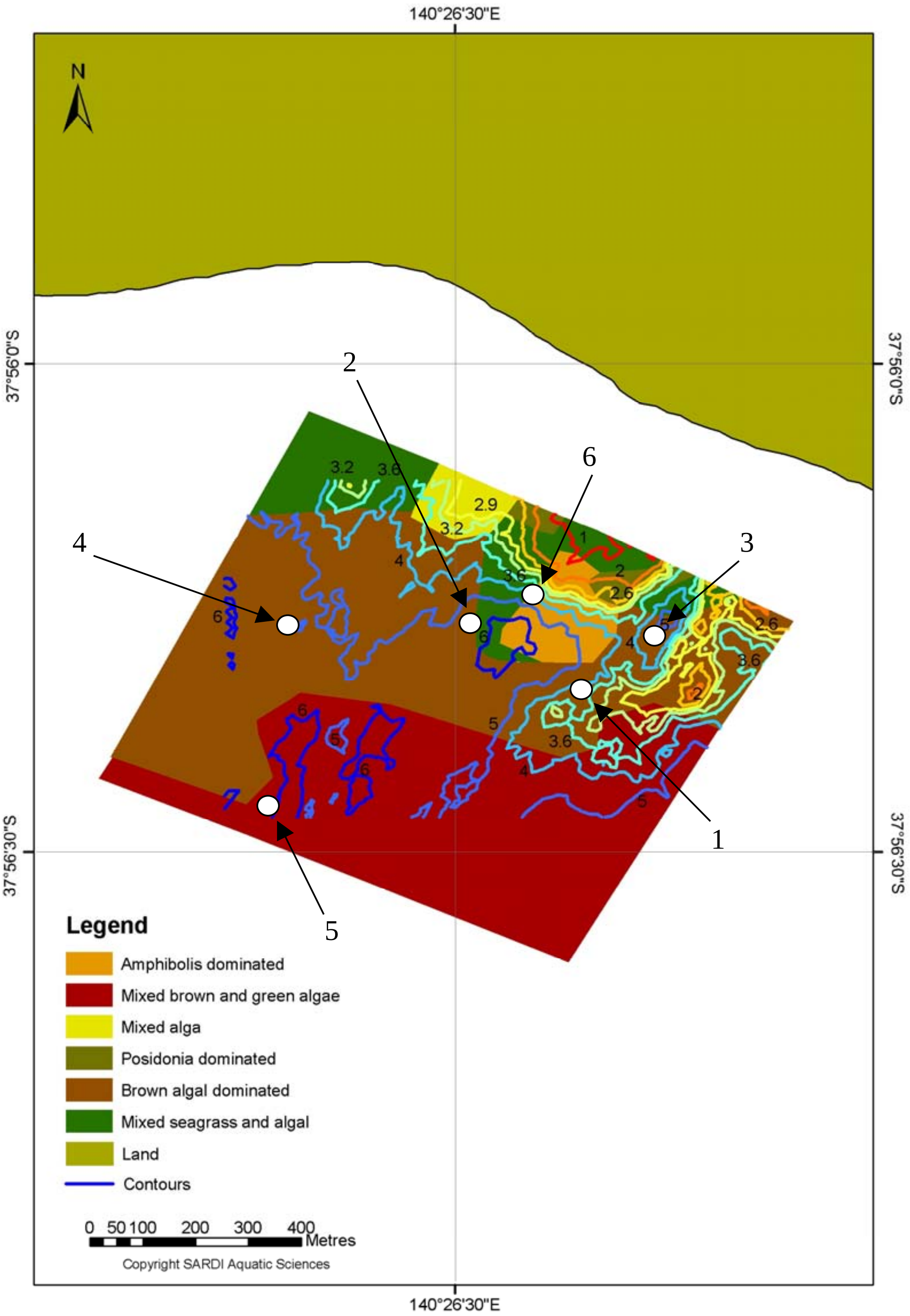

Figure 7. Map of floral assemblages in study area at Livingstons Bay

## Victoria

One Victorian site was chosen for the post settlement study located at Port Campbell, on the Great Ocean Road between Apollo Bay and Warrnambool (Figure 8). This rugged stretch of coastline, known as the 'Shipwreck Coast', has few easily accessible sites for such survey work. The site at Port Campbell was selected on the basis that it offered the most protection from southerly swells, and had reasonable numbers of lobsters in the 50-80 mm size range, required for the study.

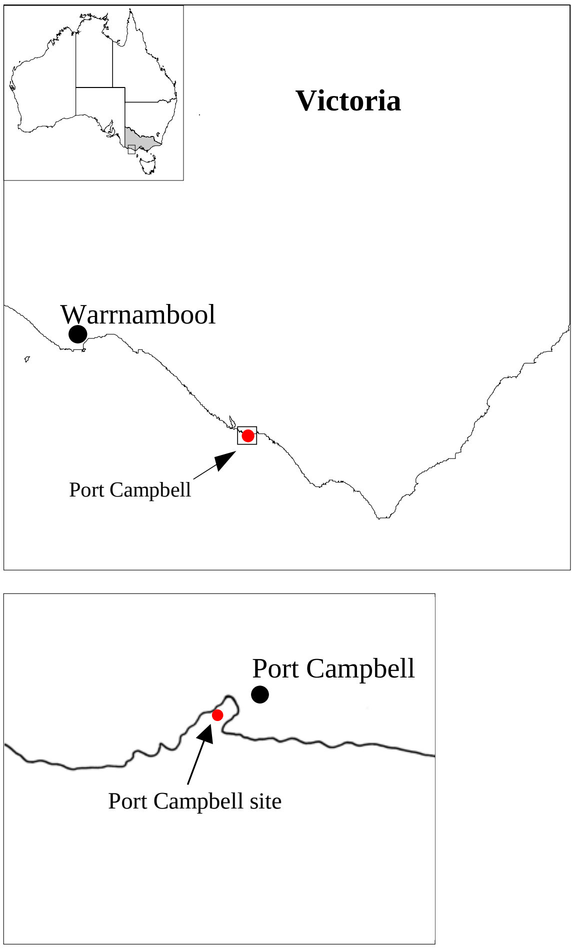

**Figure 8.** **Location of Victorian post settlement site at Port Campbell**

### Port Campbell

The site at Port Campbell (Lat. 38° 37.215' S Lon. 142° 59.456' E) is in a small, naturally formed harbour, approximately 150 m across and 300m in length, with a beach at one end and limestone cliffs running along both sides. The harbour is 9-10 m at the deepest point and is mostly a sandy bottom. Subsidence and erosion of the cliffs over the ages have formed a reef, up to 20 m wide along the harbour's western side. It is here that the study site is situated. The reef slopes gently from 1-2 m depth close to the cliff, to 6-7 m where it meets the sand. The reef was classified, based on structure, into ledging reef, boulder reef and rubble reef (Figure 9). Ledging reef was typically in the upper part of the reef, below the rock shelf, and was formed by erosion of the softer reef layers. The crevices formed were often deep and complex, hampering the capture of lobsters. Boulder reef was formed by land-slip and the breakdown of ledging reef and provided good juvenile habitat, however, the large number of bolt-holes made capture difficult. Rubble reef was generally lobster poor close to the sand margins, but provided some shelter to lobsters, higher up in the reef, particularly just below ledging reef.

The reef was heavily covered in macrophytes, with the most abundant species including the larger brown algae *Cystophora moniliformis*, *C. retroflexa*, *Perthalia cordata* and *Seirococcus axillaris*; the smaller brown algae *Halopteris* sp, *Homoeostrichus sinclarii* and *Chlanidophora microphylla*; the fleshy red algae *Areschougia congesta*, *Melanthalia obtusata*, *Ballia callitricha*, *Rhodymenia australis*, *Plocamium mertensii*, *P. angustata* and *Sonderopelta coriacea*; the coralline red algae *Amphiroa anceps* and *Cheilosporum sagittatum*; and the green algae *Caulerpa brownii*, *C. cactoides*, *C. longifolia* and *C. simplisciuscula* (Edmonds, 2002).

There were fewer lobsters at Port Campbell than at the other sites and they proved more difficult to catch due to the reef structure. There was a high dependence on mechanical devices for collecting lobsters at this site, meaning that catch rates were relatively slow. This was reflected in the low numbers of lobsters captured during the survey.

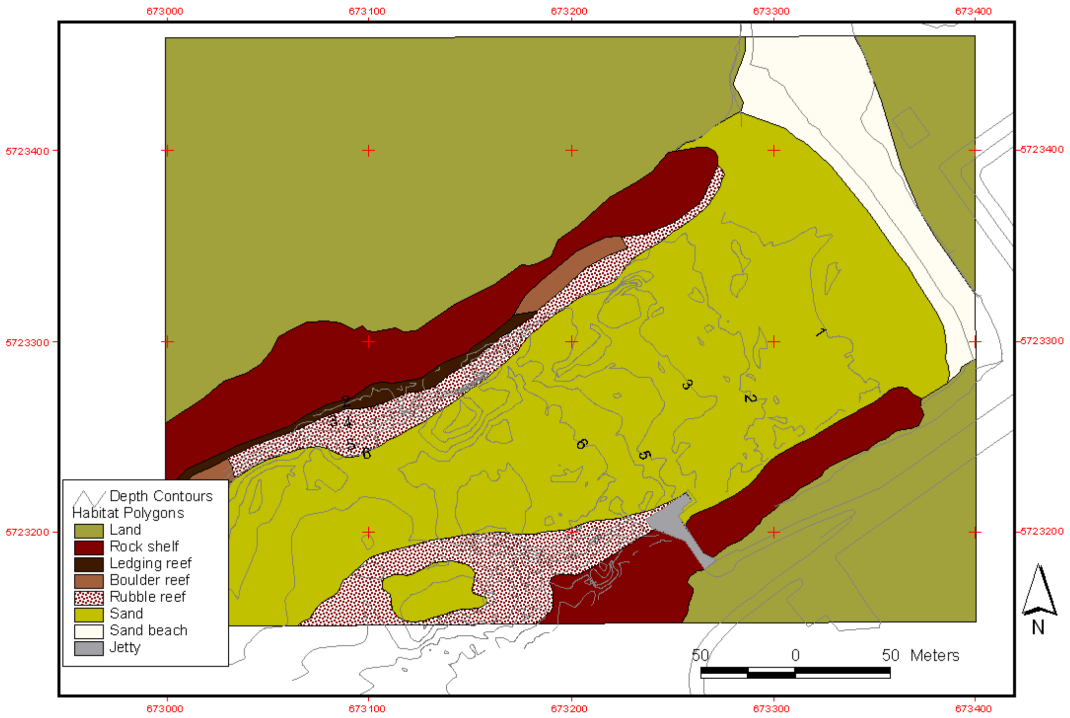

**Figure 9. Reef type at the study site at Port Campbell, Victoria.**

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# Chapter 2 - Spatial variation in condition of juvenile lobsters

## Introduction

The condition of lobsters has been examined in several studies as an indicator of growth. The condition of juvenile lobsters from research sites examined in this study was also of interest as it provided insight into density dependent suppression of growth through comparison between different sites with different density.

The influence of density on growth is of interest because it has the potential to dampen productivity benefits produced by management strategies that increase lobster abundance. For example, if recruitment were to be increased by management strategies that improve egg production – could this lead to reduced juvenile growth and lower productivity per recruit relative to current levels? This issue of density-dependent effects on exploited species has been recognised for decades as being important for fisheries modelling although it is typically difficult to examine (Beverton & Holt 1957; Sanchez Lizaso et al. 2000). Analyses presented here for *J. edwardsii* contrasted condition of juveniles from sites of different density. Density was directly manipulated by divers as described in Chapter 1.

Measuring condition in lobsters is difficult because their exoskeleton prevents any obvious external change from occurring. Several techniques have been applied that involve destruction of the animals including whole body lipid composition (Moore et al., 2000) or composition of the hepatopancreas (Musgrove, 1999). Recent research has shown that blood refractive index provides a measure of condition and can be used to predict growth increment (Musgrove 2000a; 2001; Musgrove and Babidge 2003). This development was important because it enabled condition to be quantified from a single drop of haemolymph collected quickly and without harming the lobster. These analyses of blood refractive index appear to provide a measure of condition due to the correlation between haemolymph refractive index and serum protein level (Musgrove 2001).

Oliver and MacDiarmid (2001) tested the measurement of condition from haemolymph refractive index by maintaining juveniles under differing feeding regimes. That study was especially relevant to the field sampling in Tasmania because the juveniles were of a similar size at around one year post settlement. Their results confirmed that haemolymph refractive index provides a measure of condition, although they noted that it is critical to also measure moult stage.

## Methods

Divers collected 134 juvenile lobsters from Tasmanian sites: Pigeon Holes (n=50), Glenvar Bay (n=34), and Maria Island (Point Leuseur; n=50). Density at the Pigeon Holes site was increased by the addition of 993 juveniles in addition to the 1488 resident tagged juveniles as described in Chapter 1. Information collected on each lobster included size (carapace length, CL) and sex (Figure 10).

Haemolymph pigmentation and haemolymph protein were measured according to the method of Musgrove (2001). Haemolymph samples were collected by pericardial puncture with a 1 ml syringe and 22-gauge needle. Syringes were then placed on a light box and the colour graded according to the pigment chart presented in Musgrove (2001). In additional to haemolymph colour, we collected information on moult stage through moult staging of pleopods according to the criteria described by Musgrove (2000b). This staging was done on the distal third of the pleopod, which was removed in the field with scissors.

Haemolymph protein was measured by placing a portion of the sample, around 50 μl, in a hand held refractometer to measure the refractive index as developed for *Homarus americanus* (Leavitt and Bayer, 1977). Haemolymph refractive index (HRI) was converted to serum refractive index (SRI) according to the equation: SRI= (0.9121*HRI)+0.1172. The resultant estimate of SRI was then converted to serum protein (SP; g/l) by the equation: SP=(4936*SRI)-6609.3 according to regressions developed by Musgrove (2001) for *Jasus edwardsii.*

We examined the effect of site on condition by ANOVA. In all cases, the effect of site on the variable of serum protein (SP) was examined in conjunction with the factor of moult stage, measured either as haemolymph colour or pleopod moult stage (a categorical ordinal data series in both cases). These two alternative measures of moult stage were compared by contingency analysis with significance of interaction determined by chi-square. The effects of sex and size on SP were examined by either standard ANOVA or ANCOVA respectively (with CL as the covariate).

## Results

There was no effect of size or sex on condition, either as a direct variable or through an interaction with site or moult stage (P>0.2). Consequently, all subsequent analyses ignored these factors so that data could be pooled.

Haemolymph colour and moult stage derived from pleopod were highly correlated (chi-square=27.192; P<0.0001), which indicated that either was appropriate for use as an index of moult stage for examining the effect of site on SP. Given this, we conducted subsequent analyses with haemolymph colour because of the more quantitative, less subjective nature of this data.

A two-way factorial ANOVA indicated that the effect of the interaction between site and haemolymph on serum protein was not-significant (P>0.2) so this term was then removed and data pooled. The subsequent ANOVA included only the factors of site and haemolymph colour, both of which had a highly significant effect on SP (P<0.01; Figure 11).

These results indicated that condition was highest at the Pt. Leuseur site and lowest at the enhanced site at Pigeon Holes. Pt. Leuseur was significantly different from Pigeon Holes and Glenvar Bay (P<0.01).

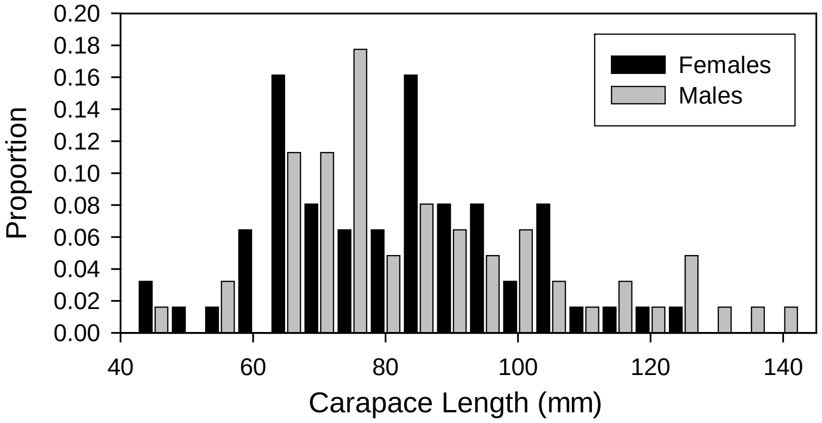

**Figure 10. Size structure of lobster samples collected by divers for condition analyses.**

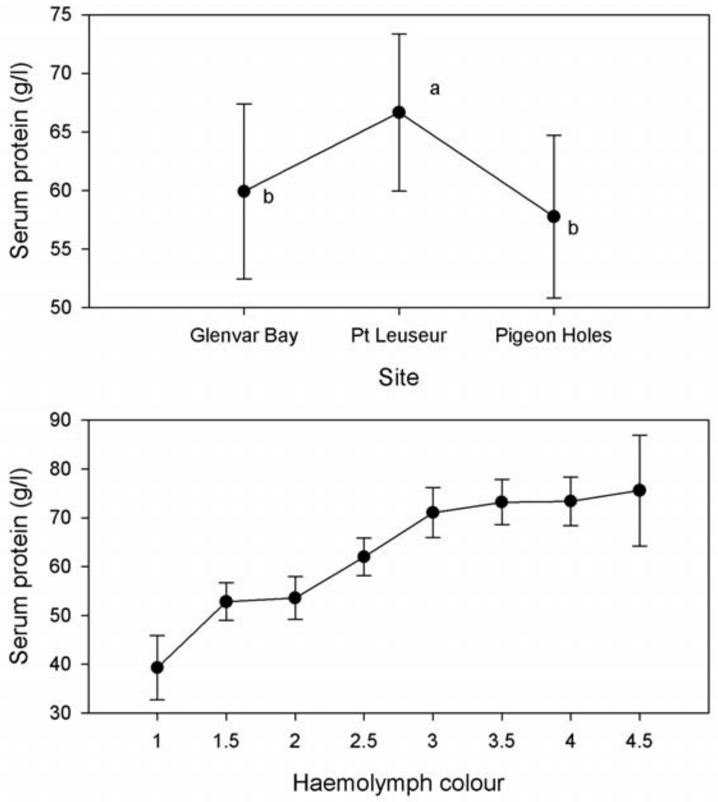

**Figure 11. Variation in serum protein between sites (upper) and haemolymph colour grades (as an index of moult stage; lower). Both relationships were highly significant (P<0.01). Significant difference between site means is indicated by letters with Pt. Leuseur (Maria Island) significantly different from the remaining sites (P<0.01).**

## Discussion

The mechanism for the apparent link between serum protein level and condition in crustaceans has been the subject of debate. It may be that the relationship is due to the metabolism of protein, so that as food availability decreases, so to does serum protein. Support for this theory comes from research on starving penaeid prawns, which utilise protein as their primary energy source (Barclay et al., 1983). An alternative mechanism for the link between condition and serum protein is that under conditions of starvation, the volume of haemolymph increases so that dilution of a constant absolute level of serum proteins is produced (Smith and Dall, 1982).

This discussion is important in the context of the present study because the effect of lower condition at some sites would be expected to be chronic shortage of food rather than acute periods of starvation as in tank experiments on condition (eg Oliver and MacDiarmid 2001). If serum protein concentration were reduced only through dilution under starvation, this effect would be expected to be less pronounced in habitats with lower levels of food supply because growth would be reduced – and thus total volume of the lobster. Support for field application of the technique comes from trials by Musgrove (2000a) where differences in condition, measured as serum protein, were observed between sites with different growth rate.

We observed higher levels of serum protein at the Point Leuseur (Maria Island) site, which was also the Tasmanian site with highest growth rate (Chapter 3). Unfortunately, no samples were taken prior to the addition of lobsters at the Pigeon Holes sites so our results are inconclusive on the effect of altered density. Nonetheless, the comparable levels of serum protein at both the Glenvar Bay and the Pigeon Hole sites indicate that the increased density at Pigeon Holes did not lead to a reduction in condition.

Although there was a trend of lower serum protein from lobsters from Pigeon Holes site relative to those from Glenvar Bay, this difference was not significant. Given that sample size was reasonable, this implies that any magnitude of decline in condition would be small, even for reasonably large increases in density.

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# Chapter 3 - Growth of $0^+$ juveniles

## Introduction

Predicting future catches is one of the most powerful pieces of information that Industry and Managers can have for sustainable management of a fishery. The further into the future a prediction can be made the greater the time for Industry to restructure or adjust financial plans.

For many species the first indication of future recruitment to the fishery is from egg production. In lobsters, which have extended larval periods, egg production is unlikely to prove a reliable indicator as there is uncertainty in larval distribution and the sources of supply of eggs in southern Australia.

The first indication of potential recruitment to the fishery occurs when the post-larval or puerulus settle on coastal reefs. In Western Australia, puerulus recruitment has been successfully used as a determinant of catches up to three years in the future (Caputi and Brown, 1986).

Unlike Western Australia, the southern rock lobster is spread over a greater range of habitat and affected by different ocean currents. In Tasmania, different regions are affected by combinations of warm and cooler ocean currents (Crawford et al., 2000). These physical features are expected to substantially impact on spatial growth rates and thus the time between puerulus settlement and subsequent recruitment to the fishery.

In addition to determining the time from settlement to recruitment, knowledge of the growth rate can also be used to identify potential bottlenecks in recruitment. For example, after a good puerulus settlement a certain size range of juveniles should be expected in the following years. Thus the cohort can be traced and changes in abundance of specific size classes noted.

Determining the growth rate of small individuals is difficult although coded wire tags have shown promise for *Panulirus cygnus*, *P. argus* and *Jasus edwardsii* (Phillips et al., 1992, Sharp et al., 2000, Edmunds, 1995). For southern rock lobster, where the settling habitat is complex, it has proven extremely difficult to find puerulus (Edmunds, 1995). In mark recapture experiments, where the animal has to be captured twice, the probability of obtaining sufficient data in such a complex habitat is minimal.

Puerulus settlement monitoring programs are used extensively in Australia and New Zealand (Booth, 1994, Gardner et al., 2001). These programs successfully use artificial habitats to attract puerulus as they search for suitable settlement surfaces.

Combining the micro-wire tag technology and the suitability of artificial substrates to attract puerulus, we explored the potential of larger reefs to support the early benthic juveniles from the settlement stage to a size where they are more readily observed on reefs and able to be caught and tagged with mini-t-bar tags (see Chapter 1). This section describes the growth of these animals.

## Methods

Six artificial reefs (see Chapter 5) were deployed in pairs at Bicheno on the East Coast and in Glenvar Bay and Iron Pot at the mouth of the Derwent estuary in Tasmania.

Puerulus, sourced from collections made during routine sampling of the Tasmanian puerulus monitoring project, were tagged with individually coded micro-wire tags using the NorthWest Marine Technology's handheld multishot tag injector (NorthWest Marine Technology, Inc., Shaw Island, Washington). Tags were inserted in the dorso-lateral musculature behind the carapace. Puerulus were then held in aerated containers for between 12 – 24 hours prior to being released into pre-drilled holes in each of the artificial reefs. The hole size was determined from previous studies evaluating the preference of settling puerulus for specific habitat type (see Chapter 5). The initial design required 10 puerulus to be added to each artificial reef each month from July to February of the following year. These puerulus were to be sourced from the existing puerulus monitoring programs. Settlement during March to June is minimal and insufficient puerulus were likely to be available. Unfortunately, puerulus settlement during this study was the lowest recorded since monitoring began in 1992 and the number of puerulus tagged and released varied depending on the magnitude of settlement that occurred each month.

Artificial reefs were to be subsampled at six monthly intervals, however the paucity of puerulus that were added to the reefs resulted in subsampling occurring at less frequent intervals. All captured juveniles were brought to the vessel where they were checked for the presence of a tag using NorthWest Marine Technology's hand held wand detector (NorthWest Marine Technology, Inc., Shaw Island, Washington). If a tag was not present, the juvenile was returned to adjacent natural reef (i.e. not the artificial reef). Tagged lobsters were brought back to the laboratory where they were measured, sexed and killed by rapid chilling prior to removal of the tag. To determine the tag number in recaptured juveniles the tag has to be surgically removed after the juvenile has been sacrificed. The number of each tag was identified using NorthWest Marine Technology's MagniViewer (NorthWest Marine Technology, Inc., Shaw Island, Washington).

At the end of the experiment the artificial reef was surrounded by a large net of 10mm stretched mesh prior to being dismantled and brought to the surface for careful checking for all remaining juveniles.

Growth rate was determined by dividing the increase in carapace length between tagging and recapture by the elapsed time during this period.

To determine seasonal growth rates the year was initially divided into warm, cold and transient seasons (when the lobsters was tagged in one season and recaptured in another). As water temperature is known to affect lobster growth, seasons were based on changes in water temperature. Daily water temperature readings are available for the Derwent Estuary and warm periods corresponded to water temperatures greater than approximately 14°C, midway between the maximum and minimum temperature found in the Estuary (Figure 12). The warm period approximated the months of December to April and cold period the months of May to November.

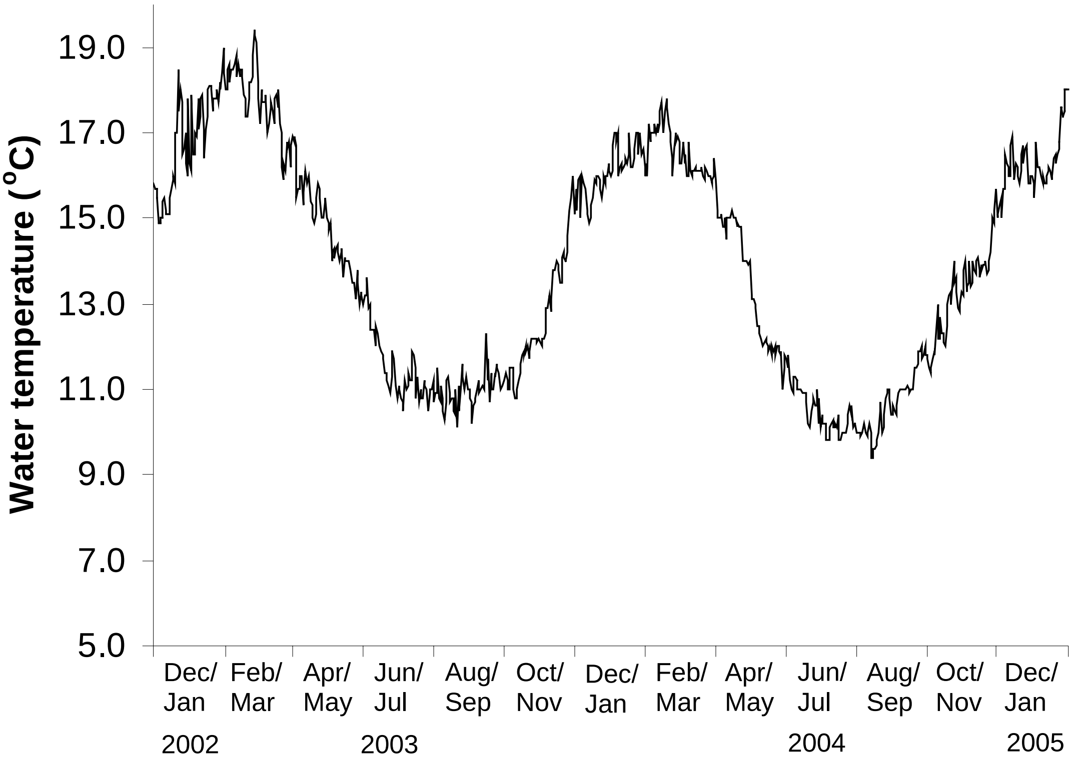

**Figure 12. Daily temperature readings in the Derwent Estuary from December 2002 to January 2005.**

# Results

Due to the timing of this project coinciding with the lowest period of puerulus settlement recorded in Tasmania, the number of puerulus tagged and released onto the artificial reefs was substantially lower than originally planned (Table 3).

During the study a total of 29 $0^+$ juveniles were found on the two artificial reefs located on reef. While it is uncertain how many of these had tags, most of the $0^+$ juveniles had disappeared within two months (Table 3, Figure 13). In contrast, the four artificial reefs located on sand in the Derwent Estuary had 456 $0^+$ juveniles sighted during the survey period. Sufficient $0^+$ juveniles were available to enable partial harvests so that a residual number remained to obtain growth from longer periods at large. A total of 130 $0^+$ juveniles were harvested from the reefs of which 79 were recaptures. This included 21 $0^+$ juveniles that were found during dismantling of the reefs. These juveniles were not found during an intensive survey of the reefs a week prior to being dismantled.

**Table 3.** **Summary of 0+ juveniles on the Tasmanian artificial reefs.**

| Site | Habitat | Number of artificial reefs | Number sighted during surveys[1] | Number tagged | Number harvested with tag | Number harvested without tag |
|---|---|---|---|---|---|---|
| **East Coast** | Reef | 2 | 29 | 229 | 0 | 0 |
| **Derwent Estuary** | Sand | 4 | 456 | 500 | 79 | 51 |

[1] Includes both tagged and non-tagged (natural settlement) $0^+$ juveniles.

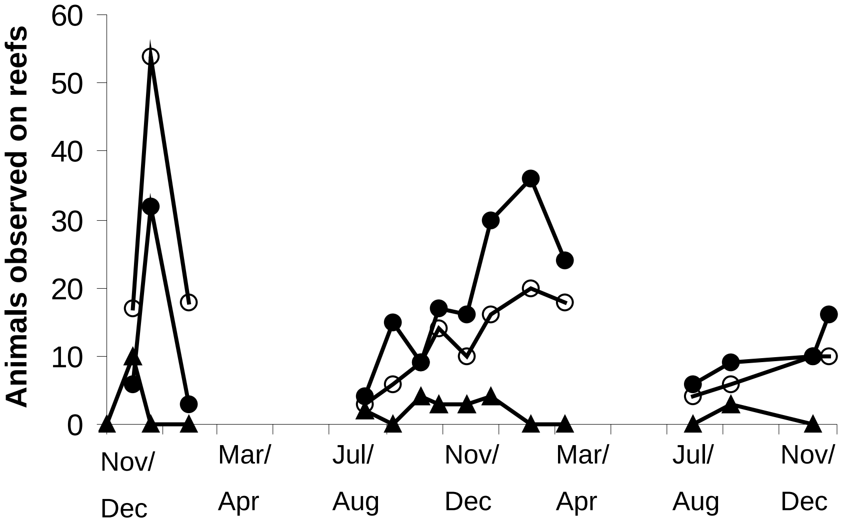

**Figure 13.** **Comparison of total 0+ juveniles (tagged and natural settlers) counts on artificial reefs in the Derwent Estuary Site 1 (closed circles), Derwent Estuary Site 2 (open circles) and Easy Coast Site 1 (closed triangles).**

Time between mark and recapture spanned a period from 33 to 355 days. During this time juveniles exhibited a mean linear growth rate of 0.078 mm CL/day. At a settlement size of 11 mm CL this resulted in juveniles of approximately 40 mm CL after 12 months (Figure 14). There was no significant difference in the growth rates of these animals due to sex (P>0.1) (Figure 15).

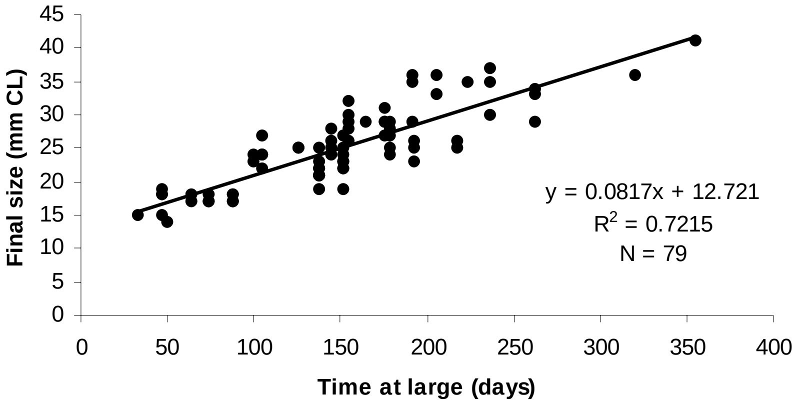

**Figure 14.** **Growth rate of juvenile *Jasus edwardsii* found on artificial reefs.**

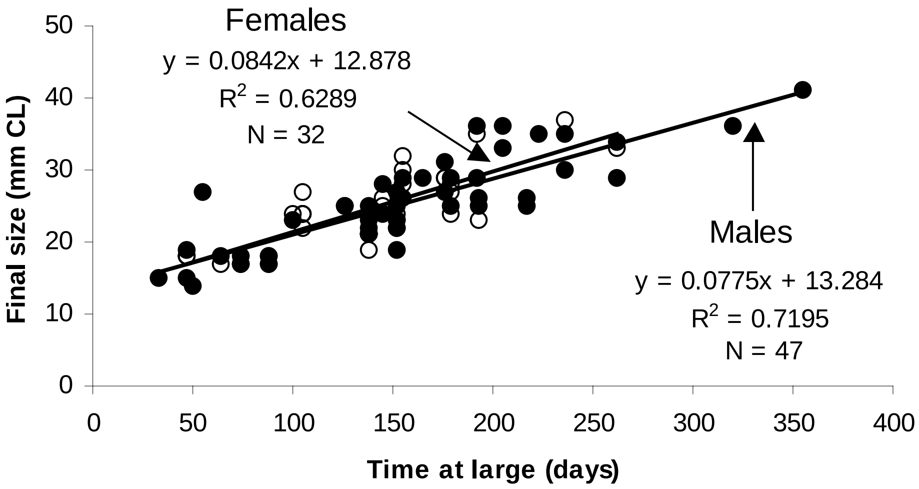

**Figure 15.** **Growth rates of male (closed circles) and female (open circles) juvenile lobsters up to 355 days after settlement.**

Juveniles that were tagged and recaptured within a continuous period of warmer or cooler water temperatures were classified as summer or winter growth respectively. Juveniles that were tagged in one water temperature period and recaptured in another were classified as summer and winter. No Juveniles were tagged and recaptured during a continuous winter period.

Growth rates were greater during periods of continuous summer periods than during periods of combined summer and winter months ($P<0.0001$) (Figure 16). The mean growth rate for a continuous summer period and a combined summer and winter period was 0.102 and 0.092 mm CL/day respectively. Assuming that the combined growth rate estimate is more characteristic of an annual cycle, the increased growth rate would result in 45mm CL juveniles after one year. Separating the growth into seasonal components also resulted in lower estimates of settlement size of 11.8 mm CL and 9.8 mm CL for summer and summer and winter combined compared to 13.3 mm CL for the combined data. The average size for all microwire tagged puerulus was 11.1 mm CL.

During 1972, 17 juveniles, initially microwire tagged as pueruli were recaptured after periods ranging from 22 to 77 days (Edmunds, 1995). Nine of these juveniles were at large during summer months and 8 during winter months. Adding these shorter term recaptures substantially improved the fit of the mean regression with a linear trend explaining 79% and 81% of the variation found in summer and combined summer and winter respectively (Figure 17).

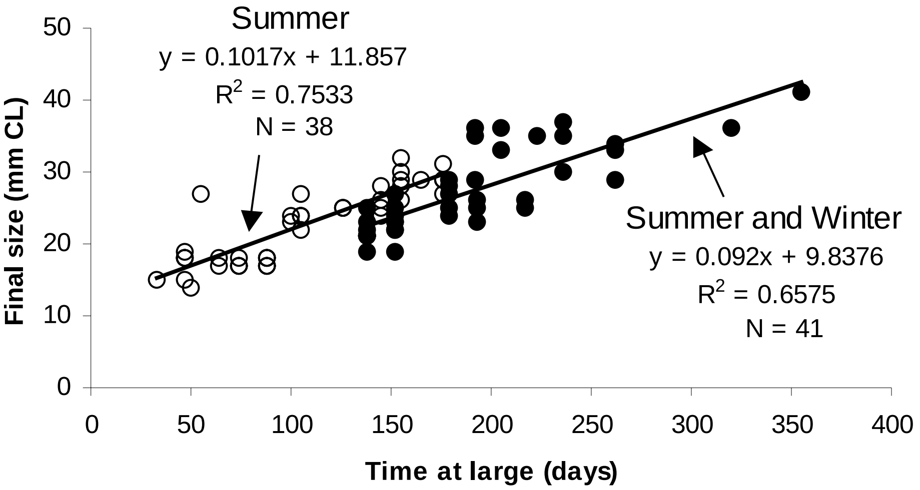

**Figure 16.** **Growth rates of juvenile lobsters caught during continuous summer periods (open circles) and during periods that contained both summer and winter periods (closed circles).**

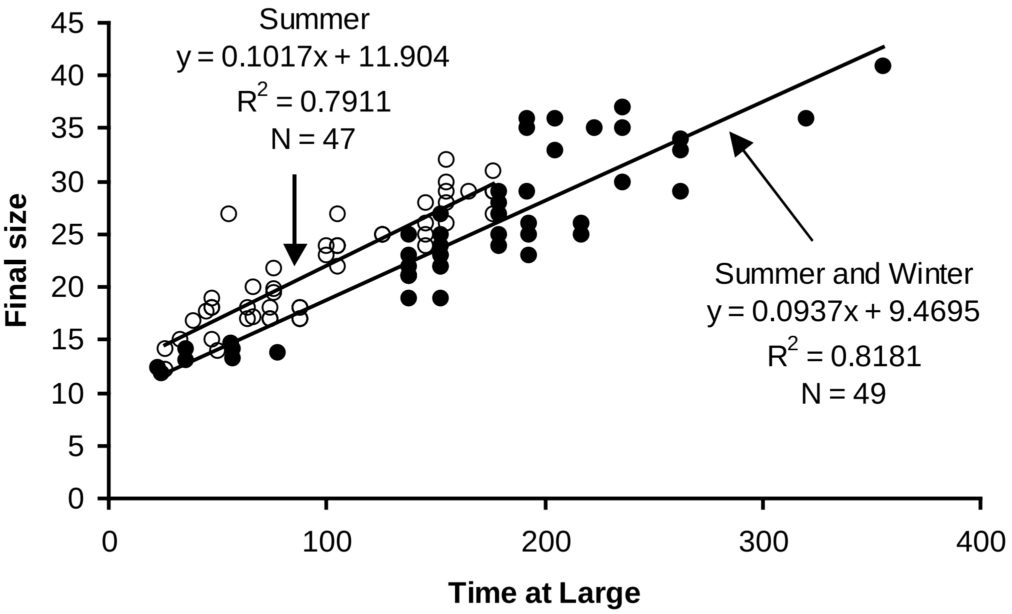

**Figure 17.** **Summer and combined summer and winter growth rates using data from this study and that from Edmunds (1995).**

The mean annual growth rate for juveniles that were at large during the transient summer and winter periods would be influenced by the proportion of this time spent during the warmer or cooler periods. For example, a juvenile that was at large for 12 months would be expected to have a mean growth rate that approximated the annual water temperatures whereas a juvenile that was at large for 6 months could have spent the majority of this time in either the cooler or warmer months resulting in a lower or higher mean annual growth rate. In our study the longer the time at large the lower the average water temperature (Figure 18). However, no puerulus were tagged and subsequently recaptured during the 4 months of winter when water temperatures average 11$^{o}$C (Figure 12). Animals at large during this period would be expected to have the lowest growth rates and alter the left-hand side (lower temperature) in Figure 18. Nevertheless, Figure 18 does demonstrate the biases that can occur when using smaller periods between tagging and recapture to estimate annual growth rates.

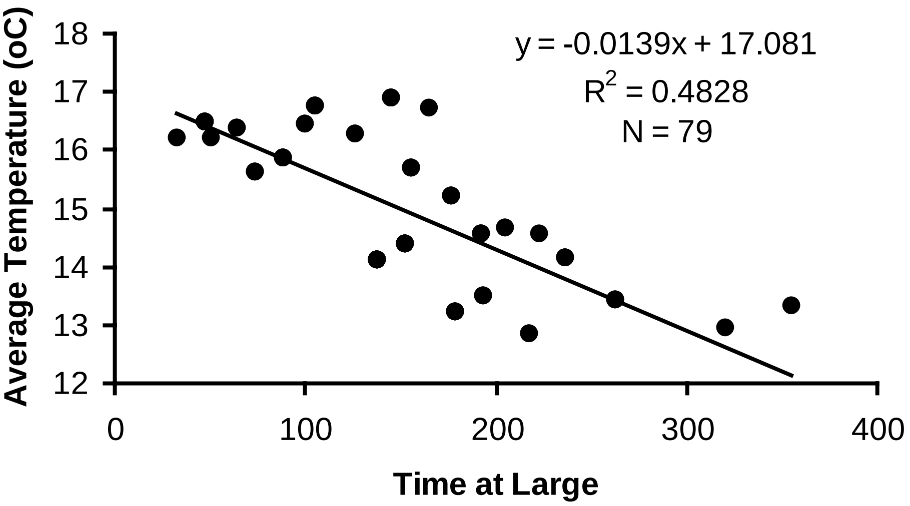

**Figure 18. Comparison of the average temperature and the period between mark and recapture.**

The longest period between tagging and recapture was 355 days and only two juveniles were recaptured after 300 days at large. To investigate the impact of time at large on water temperature and mean growth rates, the data was divided into 'time at large' bins of less than 101 days, 101 to 200 days and greater than 200 days. Smaller periods at large represented the higher temperature periods as no juveniles were tagged and recaptured during a winter period (Figure 19). The larger periods at large had lower temperatures and average temperature explained 77% of the variation found in mean growth rates.

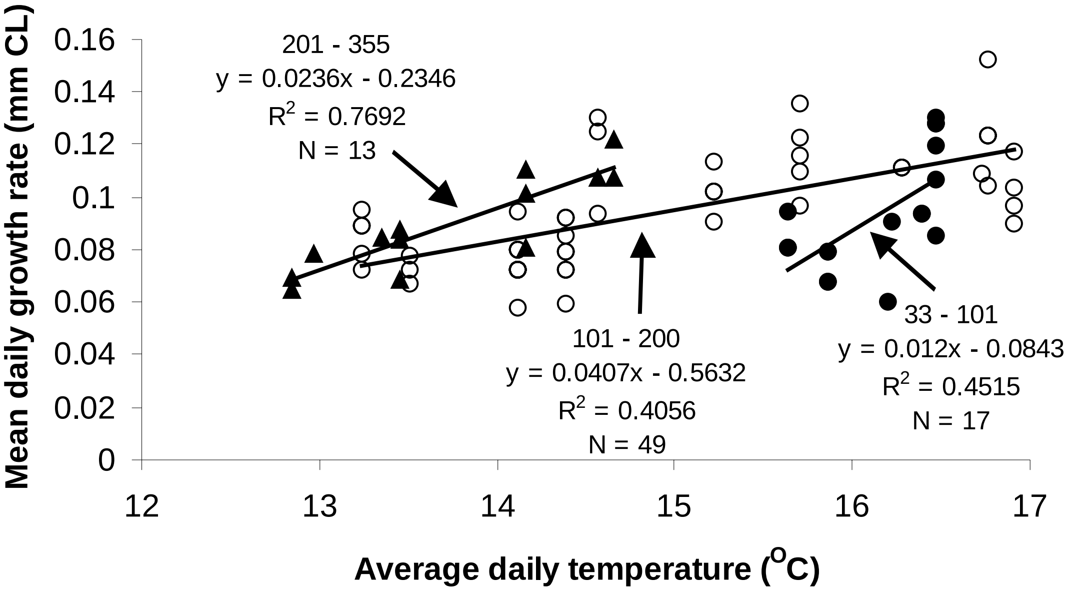

**Figure 19.** **Comparison of the average growth rates of early juvenile lobsters that experienced a range of average temperatures. Time at large are for short (33-101 days; closed circles), medium (101-200 days: open circles) and long (200-355 days; closed triangles) between mark and recapture.**

Although the time at large for the group representing the largest time at large varied from 205 to 355 days, the average temperature experience was between 12.8°C and 14.6°C. This range corresponds to the range of average annual temperatures found in the Derwent Estuary from 1st July 1995 to 30th June 2004 (Table 4). Assuming a settlement size of 11 mm CL and using the linear relationship found for the largest 'time at large' group, the estimated average size of juveniles in the Derwent Estuary after 12 months post-settlement would vary between 35 and 51 mm CL over the last 9 years. This represents an approximate 45% difference in the final size of puerulus after their first year post-settlement.

**Table 4.** **Annual estimated final size of one-year post-settlement juvenile J. edwardsii based on the average water temperature in the Derwent Estuary.**

| Year | Average water temperature (°C) | Estimates juvenile size after 12 months (mm CL) |
|---|---|---|
| 1995/1996 | 12.7 | 35 |
| 1996/1997 | 13.5 | 42 |
| 1997/1998 | 14.2 | 48 |
| 1998/1999 | 14.5 | 51 |
| 1999/2000 | 14.6 | 51 |
| 2000/2001 | 14.4 | 50 |
| 2001/2002 | 13.8 | 45 |
| 2002/2003 | 14.2 | 48 |
| 2003/2004 | 13.5 | 42 |

Annual estimates commence on the 1st July and finish on 30th June of the following year.

The size of early benthic juveniles found 12 months after the beginning of the settlement peaks in July would be a combination of the time of settlement and the water temperature experienced between settlement and June of the following year. In Eastern Tasmania there is a major settlement peak from July to September and a smaller peak from November to January (Chapter 9). Puerulus that settle later in the year would experience higher average temperatures and thus grow faster although their "time at large" between settlement and June would be reduced. By the end of June puerulus that settled between July and the start of November of the previous year would all be approximately the same size. After this period the faster growth rates do not compensate for the reduced grow out time resulting in smaller juveniles by the end of June (Figure 20).

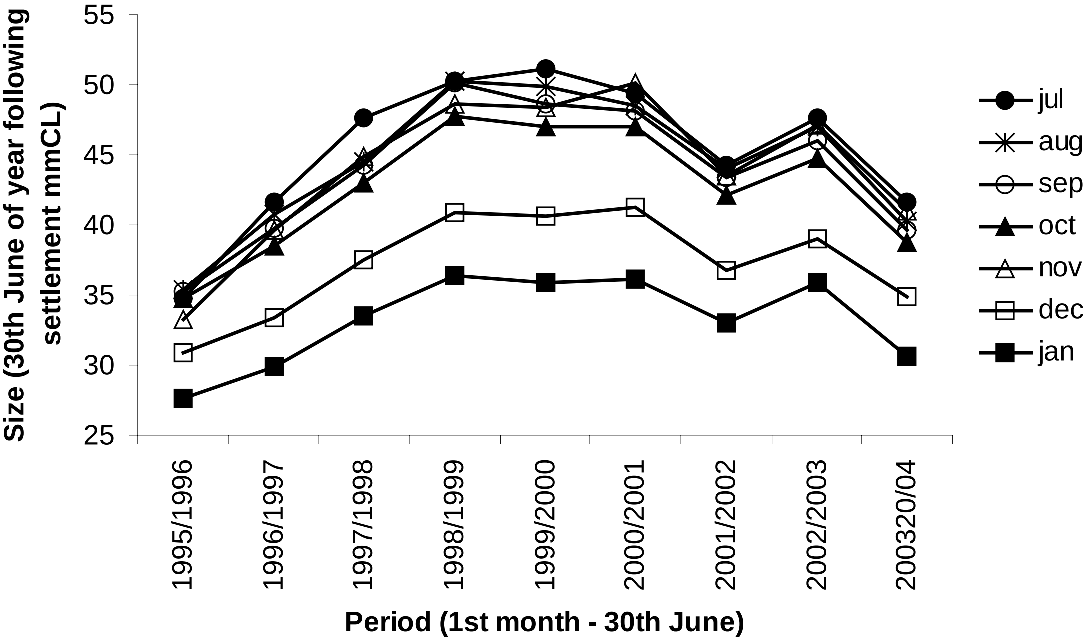

**Figure 20.** **Comparison of the final size on the 30th June following settlement at the beginning of different months for the 1995/1996 to 2003/2004 years.**

## Discussion

Artificial substrates are commonly used to attract puerulus for research purposes throughout the world (Booth and Phillips, 1994). These substrates are checked at intervals, usually months, when all puerulus are counted and removed. This study extended this concept by establishing larger artificial substrates to attract and hold puerulus and subsequent juvenile stages for periods of at least 12 months. At settlement *J. edwardsii* is considered to dwell in individual holes within the temperate reef habitat (Edmunds, 1995). Finding newly settled puerulus has proven to be exceptionally difficult as the three-dimensional structure and dense algal cover of temperate reefs provides habitat that is inaccessible to diving activity. Although puerulus settle in a hole, there appears to be no longer term association with the specific hole as Edmunds (1995) seldom found animals in the same hole during consecutive monthly surveys of a rock face in southern Tasmania. Similar behaviour has been recorded for *Panulirus japonicus* in Japan (Norman et al., 1994). This study (see Chapter 5) and a similar study in Japan (Norman et al., 1994) found that the preferred hole size for newly settled puerulus was only marginally wider than the puerulus and, as the juveniles grew, larger diameter holes were sought.

To determine the variability in growth rates it is necessary to obtain individual growth rates from a number of individuals. This involves the recapture of animals after they have been at large for specific periods in time. To determine effects of season and sex on growth, puerulus of different sex need to be monitored during different seasons of settlement. Following cohorts of animals is an option when settlement is restricted to precise periods. Settlement of *J. edwardsii* can occur throughout the year and peaks in settlement occur over several months. Thus, a cohort of juveniles would originate from pueruli that had settled at unknown times. Tagging puerulus and early stage benthic juveniles with individually coded microwire tags has been successful for *P. cygnus* (Phillips et al., 1992), *J. edwardsii* (Edmunds, 1995) and *P. argus* (Sharp et al., 2000). Although these previous studies were conducted over months, our study confirmed the potential of microwire tags to enable longer term studies to be undertaken.

The use of artificial structures that contain holes of the appropriate size required by puerulus and juveniles and, that can be dismantled to check all potential habitats, was considered the best option for successfully recapturing tagged puerulus after being “at large” for up to 12 months. The amount of natural settlement that occurred on the artificial reefs during the study confirmed that the reefs were appropriate settlement habitat. As there was no trend in increasing numbers of puerulus settling during the study there appeared to be no impediment to settlement associated with conditioning of the artificial reefs. However, the lack of recaptures from artificial reefs placed on reef as opposed to sand is intriguing. By being in immediate contact with the reef, puerulus placed on the artificial reef may have been exposed to predation by reef-associated predators that would not be present on artificial reefs that did not have a direct connection to the reef. With the exception of larger lobsters, most of the predators of juvenile lobsters (Oliver et al., 2005) were found on the artificial reefs located on sand. Another explanation is that the puerulus emigrated from the artificial reefs to the natural reefs. Although each reef was connected via supporting legs to the substrate where it was placed, these supports were a minimal component of the structure and it is unlikely that puerulus would have used these legs to emigrate to the surrounding substrate. We hypothesise that the puerulus could sense the surrounding habitat and swam to the adjacent reef. The cues that enable puerulus to swim from oceanic waters to coastal reefs are unknown. Chemosensory cues could be used by pueruli placed on artificial reefs to determine the proximity of preferred habitat.

The poor natural settlement during this study resulted in fewer puerulus being available to add to the artificial reefs. This, in turn, resulted in fewer harvests than originally planned. Despite these constraints, we were able to obtain the first estimates of growth of *J. edwardsii* for the first 12 months post-settlement. Growth rates were fast with animals reaching between 35 and 51 mm CL in their first year after settlement depending on the water temperature during this period. Sharp et al., (2000) also found that the first year’s growth of newly settled *P. argus* was linear and fast with a mean size of 41.6 mm CL after12 months post settlement. Norman et al., (1994) reported a size range of 35 – 40 mm CL for *P. japonicus* after 12 months post settlement. Adult lobsters show substantial differences in growth rates between sexes. This is associated with the utilisation of energy for growth, gonad development and metabolism with females requiring greater amounts of energy to produce eggs. Prior to maturity, metabolism and growth are considered to be similar for both sexes. Our results found no differences between male and female growth rates in the first year post-settlement. This was also shown for *P. argus* in Florida (Sharp et al., 2000). Sharp et al., (2000) also found seasonal differences in growth rates with summer growth rates being up to 40% greater than winter growth rates. Although no growth rates were obtained for winter periods during this study, we found an 8.5 % difference between summer and combined summer and winter growth rates. Although a variety of variables could have accounted for seasonal effects on growth rates including temperature, quality and quantity of food, aquarium trials have found that temperature significantly increases growth rates in *J. edwardsii* up to 18 – 20 $^0$C before inhibiting growth rate at higher temperatures (Thomas et al., 2000).

For *J. edwardsii* in the wild, we found that average water temperature explained over 75% of the variability in mean growth rates of animals that had been at large for most of the year and had experienced both summer and winter water temperatures. For animals that were at large for less than 200 days, water temperature explained less than 50% of the variability in mean growth rates, presumably due to the differing amounts of time that juveniles had been exposed to summer and winter temperatures.

Understanding the impact of water temperature on growth rates is important for predicting future recruitment to the fishery. During the past 9 years there has been a 15% difference between the mean water temperature in the Derwent Estuary. This change has resulted in a 45% difference in the final size of juveniles after 12 months post settlement. In southern Tasmania where there is an annual moult by lobsters at the minimum size limit, water temperature could result in the lag time between puerulus settlement and recruitment to the fishery being in excess of 1 year.

The timing of settlement within a year is also important in determining the timing of recruitment to the fishery. With substantial changes in growth rates depending on exposure to summer or winter water temperatures, puerulus settling at different times within a year would grow at different rates. Within a 12 month period starting in July, when the largest settlement peak in *J. edwardsii* occurs, puerulus that settle between July and October would be of similar size at the end of June of the following year. After October, the decreased time available for growth is not compensated for by the summer water temperatures and puerulus reach a smaller final size by the end of June. As July to October is the largest of the settlement peaks in Tasmania (see Chapter 9), all these animals would be expected to contribute to a similar recruitment peak in the fishery.

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# Chapter 4 - Growth of $1^+$ and older juveniles

## Introduction

Growth of juvenile *J. edwardsii* between 50 and 70 mm CL is not well studied, largely due to research being driven by the need for stock assessments of wild fisheries. These are generally based on data from commercial fishing gear, which is designed to minimise catches of undersize lobsters using escape gaps and larger mesh sizes. Juvenile lobsters have proven to be difficult to catch using pots or traps, and modification of commercial fishing gear by reducing mesh size and closing escape gaps reduces the smallest size of lobsters caught to around 60mm carapace length (CL) (Hobday and Flint 2000). Thus, the current length-structured fishery models used for *J. edwardsii* in Victoria and Tasmania commence modelling of growth at 80mm (Hobday and Punt 2001, Punt and Kennedy 1997).

To be able to link puerulus settlement with recruitment in these models, growth estimates from puerulus to the lowest reliable size group obtained in traps is required. Edmunds (1995) suggested that juveniles change from a solitary behaviour to a more social behaviour around 35 – 40 mm CL and aggregate in groups. This size also corresponds to the lower size range that juveniles are found in sufficient numbers on reefs to reliably tag.

Previous studies on the growth of juvenile *J. edwardsii* have been undertaken in culture experiments where the aim is to maximise growth through manipulation of diet, density and environmental variables (eg. Temperature) for aquaculture. (Jeffs and James, 2001; Crear et al. 2000; James and Tong, 1997, Hooker et al. 1997).

This study aimed to investigate the growth of juvenile lobsters from 40 to 80 mm CL and relied on tag and release by divers rather than potting or trapping techniques normally used for pre-recruit and adult growth studies.

## Methods

The study sites and lobster capture methods are described in Chapter 1. In Tasmania, Point Leuseur was an east-coast oceanic site, Glenvar Bay and Pigeon Holes were located in a more sheltered environment within the mouth of the Derwent River. The density of lobsters at Pigeon Holes was increased by translocation of lobsters from adjacent regions of Glenvar Reef, Kings Pier, Royal Yacht Club and Pigeon Holes Strip (Figure 21). The South Australian sites included six adjacent areas in Livingstons Bay and a nearby site in Gerloffs Bay. The Livingstons #5 and the Gerloffs Bay sites had lobsters translocated from the Livingstons Bay sites and Gerloffs Bay respectively to increase density (Figure 21Figure 21). The Port Campbell site was only used to investigate growth and no density manipulations were carried out in Victoria.

In the analysis, releases and recaptures were grouped into three categories for each site:-

i. *All.* Included all lobsters where at least one release or recapture occurred at a site.
ii. *Resident.* Only lobsters that were *initially captured*, released and recaptured at a site.
iii. *Translocated*. All lobsters moved to a site as part of density manipulations.

To investigate the moult increment and frequency of moulting, recaptures were separated into three size classes based on the initial size of tagging. The smallest size range followed on from the largest size grouping found in the $0^+$ juvenile growth section and included lobsters from 37 to 50 mm CL. The medium size range included lobsters from 51- 70 mm CL and the largest size range included lobsters greater than 70 mm CL. Surveys were undertaken at approximately 6 monthly intervals although this varied due to weather (Chapter 1).

The moult increment was determined by identifying principal modes in the frequency distributions of increments for recaptured juveniles that were at large for less than 6 months. The frequency of moulting was similarly investigated by looking at recaptures at liberty for up to one year. Due to the small recapture sample sizes at some sites, only Pigeon Holes and Livingstons could be analysed for all size groupings and time periods.

To determine the average annual growth rates several stochastic versions of the von Bertalanffy-Fabens growth model were used (Troynikov 1998). The outputs of the data parameterisation were means and distributions of the length-increments for given lengths at release and time at liberty. These models were used for calculating growth transition matrixes for rock lobster stock assessment population dynamic model (FRDC project 2004/037). The deterministic von Bertalanffy-Fabens growth parameters $l_\infty$ and $k$ were estimated for each sex at each site. Since the stochastic growth models are in the form of probability density functions the likelihood- ratio test was used for comparison of growth between different sites.

Originally, the von Bertalanffy-Fabens growth model was developed for populations with continuous growth, when a small time at liberty will produce a small length increment. However rock lobster data demonstrate that for very short time at liberty the increment in size can be zero or significant, depending on whether the lobster has moulted whilst at liberty. In this situation the stochastic von Bertalanffy-Fabens growth model can only use data that have time at liberty more than about 6 months. Unfortunately the need to set a minimum time at liberty causes considerable data loss and highlights the need for development of growth models that are better suited to crustaceans.. A minimum time at liberty of 0.6 years provided a balance between data loss and ability to fit the data and was used in all the stochastic model analyses for this study.

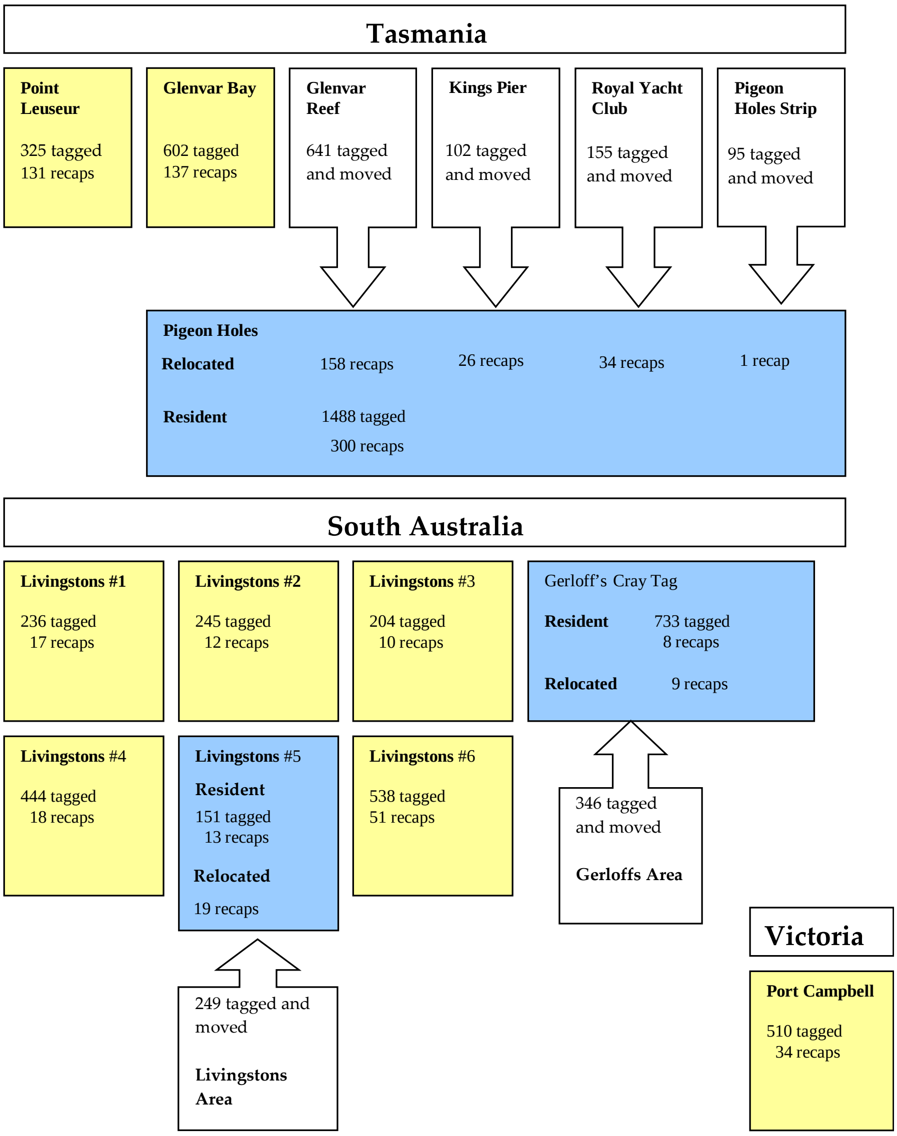

**Figure 21. Numbers of lobsters tagged and recaptured for individual sites within each State. Unshaded boxes represent source sites for translocations, yellow boxes show normal study sites and blue represent sites where density was increased.**

# Results

## Recapture rates

A total of 7,064 lobsters were tagged and released with an overall recapture rate of 14% (Table 5).

In Tasmania, the highest recapture rate of 40% was at Point Leuseur with Glenvar Bay and Pigeon Holes having recapture rates of 20-25% (Table 5). The higher recapture rate at Point Leuseur was related to the comparatively low amount of cryptic habitat enabling greater access by divers, and the isolation of the reef by surrounding sand, which restricted movement of tagged lobsters from the study area. To demonstrate this, the number of tagged to untagged lobsters was recorded on the last day of diving fieldwork at Point Leuseur and Pigeon Holes. At Point Leuseur, 60% of the lobsters captured had already been tagged while on the last day at Pigeon Holes, only 24% had been tagged indicating the efficiency of capture at Point Leuseur related to a more open and accessible habitat. It is not known why there was a low recapture rate of Pigeon Holes lobsters relocated from Pigeon Holes Strip (1%, Table 5).

**Table 5.** **Number of releases, recaptures and recapture rates for each site and translocation group.**

| State | Site | Number tagged | Number recaptured | % recaptured |
|---|---|---|---|---|
| **Tasmania** | Point Leuseur | 325 | 131 | 40% |
| | Glenvar Bay | 602 | 137 | 23% |
| | Pigeon holes Resident | 1,488 | 300 | 20% |
| | Pigeon Holes Relocated from Glenvar Reef | 641 | 158 | 25% |
| | Pigeon Holes Relocated from Kings Pier | 102 | 26 | 25% |
| | Pigeon Holes Relocated from Royal Yacht Club | 155 | 34 | 22% |
| | Pigeon Holes Relocated from Pigeon Holes Strip | 95 | 1 | 1% |
| | **Total** | **3,408** | **787** | **23%** |
| **South Australia** | Livingstons #1 | 236 | 17 | 7% |
| | Livingstons #2 | 245 | 12 | 5% |
| | Livingstons #3 | 204 | 10 | 5% |
| | Livingstons #4 | 444 | 18 | 4% |
| | Livingstons #5 Resident | 151 | 13 | 9% |
| | Livingstons #5 Relocated from Livingstons Area | 249 | 19 | 8% |
| | Livingstons #6 | 538 | 51 | 9% |
| | Gerloffs Resident | 733 | 8 | 1% |
| | Gerloffs Relocated from Gerloffs area | 346 | 9 | 3% |
| | **Total** | **3,146** | **157** | **5%** |
| **Victoria** | Port Campbell | 510 | 34 | 7% |
| **Total** | **Total** | **7,064** | **978** | **14%** |

Recapture rates of translocated lobsters were similar to that of resident lobsters in all cases except for a low number of lobsters relocated from Pigeon Holes strip to pigeon Holes. (Table 5). The Pigeon Holes site had 1,488 resident lobsters tagged and was increased in density by 1,073 from nearby reefs.

South Australian recaptures were much lower than in Tasmania, ranging from 1-3% at Gerloffs to 4-9% at the Livingstons sites. These lower recapture rates again reflect the more cryptic nature of the habitat in South Australia and the fact that the sites were not significantly isolated from other reef structures reducing their ability to retain lobsters.

In Victoria, the recapture rate was 7% (Table 5) which was similar to that in South Australia, again indicating the cryptic nature of the habitat and increased difficulty to capture and then recover tagged lobsters in a complex reef system.

## Growth increments

For recaptures within 6 months of release at Pigeon Holes, the most common increment for release lengths less than 70 mm was 4 mm for females and 5 mm for males. At Livingstons the most common increment for females was 3-4 mm CL. A 10 mm CL increment was predominant for males less than 50 mm CL, indicating 2 moults within the 6 months at large, while a 5 mm CL increment was noted for those greater than 50 mm CL. In general the moult increments appeared slightly higher at Pigeon Holes (4-5 mm CL) than at Livingstons (3-4 mm CL).

Pigeon Holes recaptures up to one year after release, in the smallest size range (release length less than 50 mm CL), males showed the highest frequency of moulting at an increment of 10-12 mm CL, representing two moults. The next main increment group was 17-19 mm CL representing a further 2 moults (Figure 22). Males in the smallest size range were therefore probably moulting 4 times per year. Similarly, females in the smallest length range, showed increment frequencies at 4, 8-12, 15-17 and 20 indicating at least 4 moults per year (Figure 22). In the mid size range (50-70 mm CL), the main increment for females was as 5 mm CL with minor peaks at 11, 14 and 16 mm CL (Figure 22), indicating 2-3 moults per year.

This reduction in moult frequency is due to some females in this size range becoming mature. For the mid size range, male increments were dominated by the 5-7 mm CL size classes with peaks following at 10-14 mm CL and 17 mm CL (Figure 22), suggesting 2-3 moults per year. For the largest size range (>70 mm CL), female increment frequencies were mainly 3-5 mm CL (Figure 22), indicating only one moult per year. This is consistent with estimates that 50% of females in this area reaching sexual maturity at 74 mm CL. Males in the largest size range showed a broad spread of increments indicating that moults were occurring at a higher frequency than the females (Figure 22).

At Livingstons, recaptures of males up to one year after release in the smallest size range showed the highest frequency of moulting at 8, 10, 13-14 and 17 mm CL (Figure 23). Assuming the initial peak at 8 mm CL represents two moults, this size range is probably moulting 4-5 times per year. Females in the smallest size range showed peak increment frequencies at 4, 6 and 9 mm CL or 3 moults per year (Figure 23). Increments in the mid size range for males were at 4, 7, 9, 12-13 and 16 mm CL (Figure 23), suggesting 4-5 moults per year. Females in the mid size range appeared to be moulting at least 3 - 4 times per year with peak increments at 3, 6, 9 and 11-13 mm CL (Figure 23). For the largest size range, male increment frequencies were 4-6, 8, 12 and 16 mm CL suggesting around 4 moults per year (Figure 23). In contrast, female increment frequencies peaked at 3 and 6 mm CL (Figure 23) or 2 moults per year, with the reduction in moult frequency due to females maturing at around 88 mm CL.

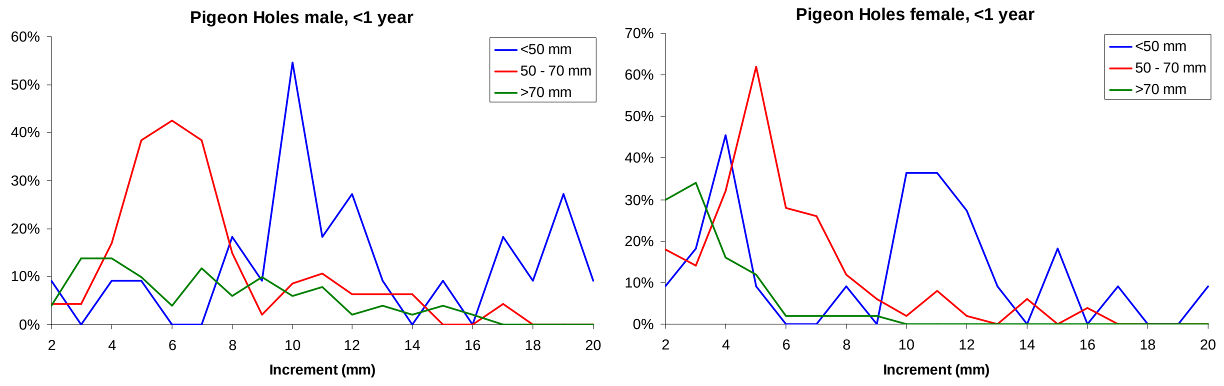

**Figure 22.** **Frequency of growth increments of male (left) and female (right) lobsters for size ranges of 0.37 – 50 mm CL, 51 – 70 mm CL and >70 mm CL. All growth increments have occurred within twelve months of tagging at Pigeon Holes.**

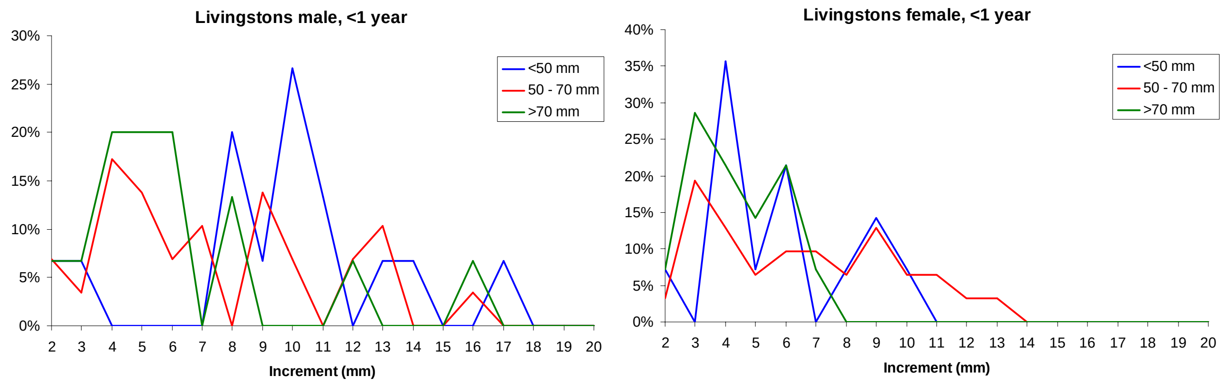

**Figure 23.** **Frequency of growth increments of male (left) and female (right) lobsters for size ranges of 0.37 – 50 mm CL, 51 – 70 mm CL and >70 mm CL. All growth increments have occurred within twelve months of tagging at Livingstons.**

## Growth by State

The stochastic growth model was not able to estimate mean growth for small times at liberty (<0.3 years). Using data from smaller times at liberty increased the number of useable recaptures, but also increased the number with no growth (no moult) and therefore lowered the estimates of mean growth at the sizes considered. A minimum time at liberty of 0.6 years was chosen as a balance between data loss and ability to fit the data and was used in all the stochastic model analyses within this study to provide consistency across all study sites.

The annual estimation of growth for each State using the stochastic model show substantially higher growth rates for males than females. At 50, 60 and 70 mm CL, mean annual growth for males was 5-6 mm higher than for females in South Australia and Tasmania (Figure 24). South Australia mean annual growth was slightly higher than Tasmania for both sexes and similar to female growth in Victoria (Figure 24). The small number of Victorian recaptures at Port Campbell resulted in poor estimation of growth from male recaptures (Figure 24).

Likelihood ratio comparison of state-wide growth showed no significant differences ($P > 0.05$) in growth for either sex between South Australia and Tasmania and similarly between females in Victoria and the other two states.

### Growth parameters

Likelihood estimates of von Bertalanffy growth rate K and maximum length parameter $L_{\text{infinity}}$ were estimated for each state and are provided in Table 6.

Size transition matrices were calculated for males and females in each state(Appendix 3). Currently, the size transition matrices used in the Victorian and Tasmanian length-structured models commence at 80 mm CL but this work has extended the matrices down to 20 mm CL.

**Table 6. Estimates of the von Bertalanffy growth parameters for each state. (Minimum time at liberty 0.6 years)**

| State | Sex | n | Distribution model | K | Std Dev (%) | $l_\infty$ (mm) |
|---|---|---|---|---|---|---|
| **South Australia** | Female | 32 | Log normal | 0.249 | 50 | 112.6 |
| | Male | 44 | Weibull | 0.220 | 48 | 151.9 |
| **Tasmania** | Female | 147 | Weibull | 0.205 | 48 | 125.4 |
| | Male | 106 | Weibull | 0.156 | 34 | 178.2 |
| **Victoria** | Female | 15 | Gamma | 0.262 | 53 | 108.8 |

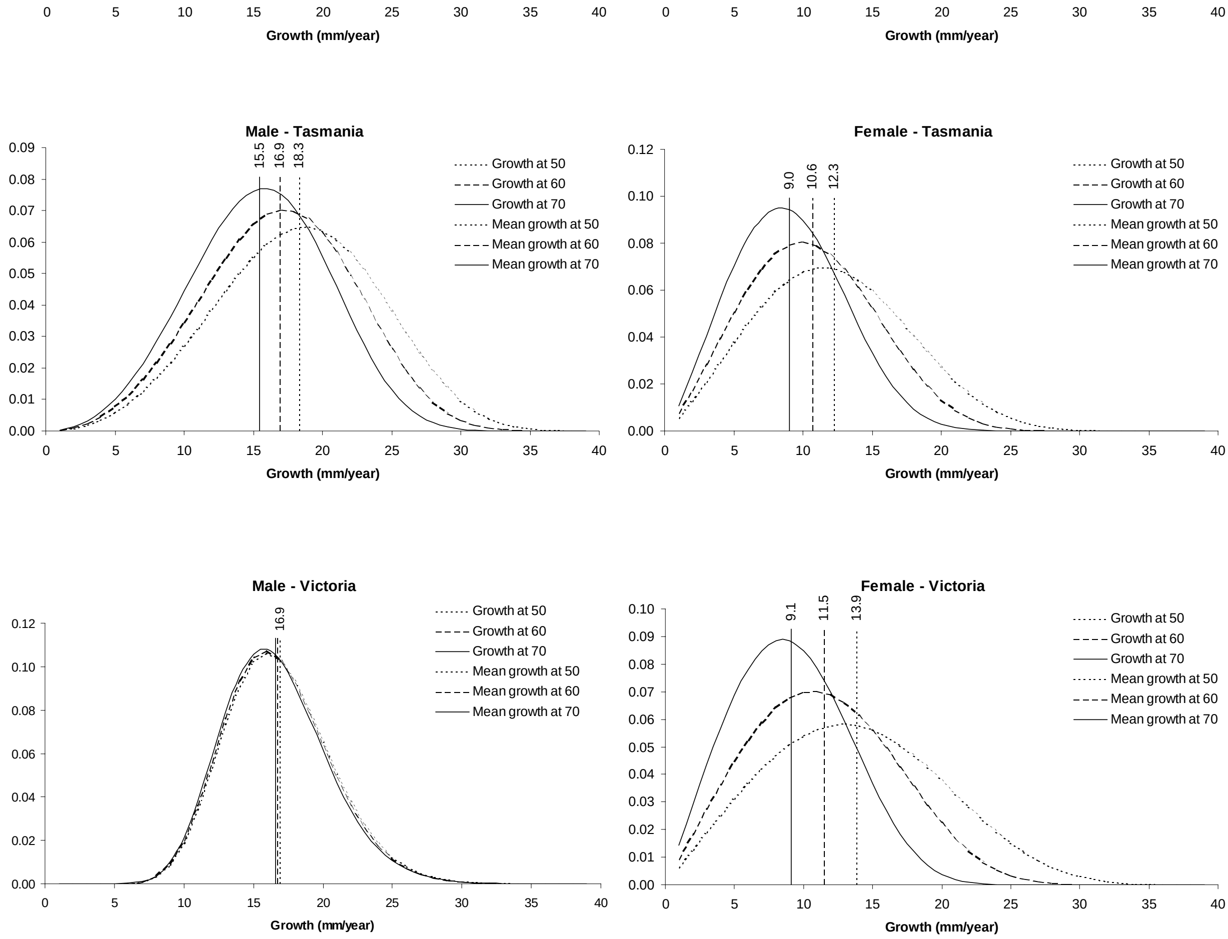

**Figure 24. Comparison of growth (mm/year) at 50, 60 and 70mm CL for each of the three States sampled. Vertical axis represent the probability density function.**

## Growth at sites

### South Australia

The number of recaptures each of the Livingstons sites was too small at to enable estimation of growth for each site. Livingstons #6 had the most recaptures but gave unreliable results for males and failed to estimate mean growth for females. Similarly, no growth estimate was possible for the density-enhanced site at Livingstons #5. Various combinations of data from Livingstons were analysed but failed to estimate growth rates. Combining all six sites (Livingstons #1-6) produced the only meaningful growth estimates and these data were used in the following analyses.

At 50, 60 and 70 mm CL, Livingstons #1-6 males were growing around 6 mm/year faster than females (Figure 25). At Gerloffs, only 7 females were recaptured and estimation of mean growth was not possible. No significant difference in male growth was observed between the two South Australian localities (Figure 25).

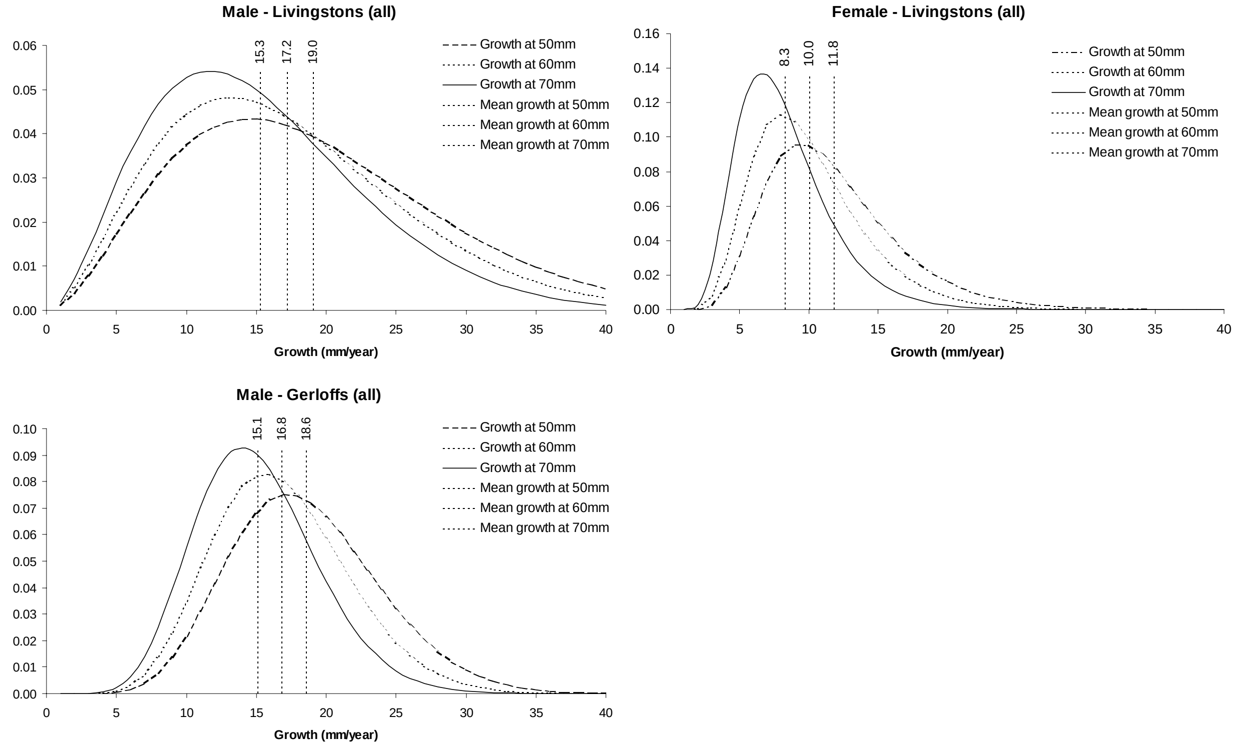

**Figure 25. Estimates of growth by for the South Australian combined Livingstons #1-6 sites (top) and Gerloffs male (bottom) using the stochastic model. Time at liberty >0.6 years. Vertical axis represents probability density function.**

### Tasmania

Growth at Pigeon Holes was similar to the other Tasmanian sites with male growth around 7 mm/year higher than females for each size group estimated. The large number of recaptures from Pigeon Holes provided well defined probability distributions (Figure 26), and allowed a comparison to be made of growth between the all, resident and translocated groups of lobsters. No significant differences in growth were found between any of these groups (Table 7) enabling pooling of data in subsequent analyses.

**Table 7. Comparison of growth at Pigeon Holes between all combinations of recapture groups using a likelihood ratio test.**

| Recapture group | Sample | n | Chi$^2$ | P |
|---|---|---|---|---|
| All<br>Resident | Males | 69<br>44 | 0 | ns |
| All<br>Resident | Females | 104<br>57 | 1.126 | ns |
| Resident<br>Translocated | Females | 57<br>37 | 4.913 | ns |
| All<br>Translocated | Females | 104<br>37 | 2.170 | ns |

There were insufficient recaptures at Glenvar Bay to provide stable estimates of growth. Growth at Pt. Leuseur was the highest observed in the study with males averaging 17.5, 19.7 and 21.8 mm CL per year and females averaging 16.3, 14.1 and 11.9 mm CL per year at 50, 60 and 70 mm CL respectively (Figure 26). Male growth at Pt. Leuseur was not significantly different to Pigeon Holes, and female growth was significantly higher than at Pigeon Holes (p<0.005, Table 7).

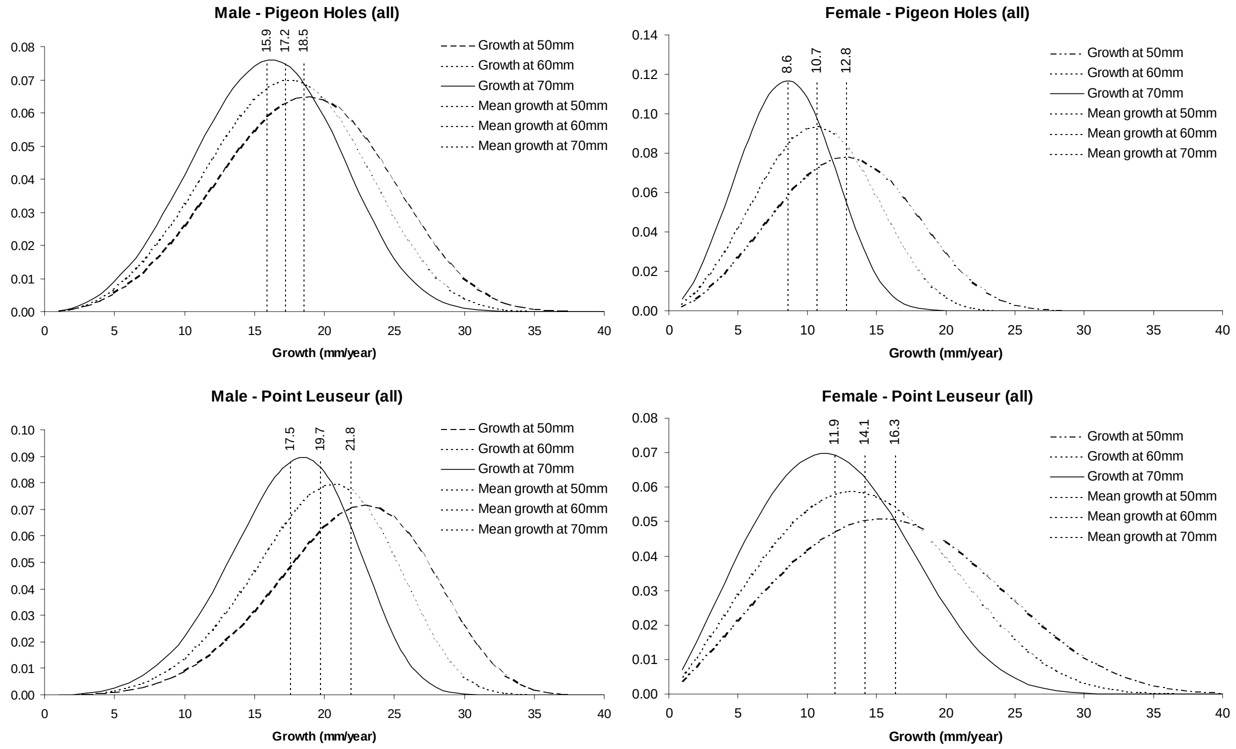

**Figure 26. Estimates of growth for the Tasmanian sites, Pigeon Holes (top), and Point Leuseur (bottom). Time at liberty >0.6 years.**

### Victoria

A stable estimate of growth was only possible for females because of the low number of male recaptures (Figure 24). Females were growing at an average of 13.9, 11.5 and 9.1 mm/year at 50, 60 and 70 mm CL respectively.

## Growth comparison

The highest male growth rate was at the Tasmanian Point Leuseur site (Figure 27). Of the Tasmanian sites with sufficient recaptures and reliable growth estimates, female growth at Point Leuseur was significantly higher than at Pigeon Holes; and male growth was significantly higher at Glenvar Bay than at Pigeon Holes and significantly lower than at Point Leuseur (Table 8).

Comparisons of growth between sites in the different states showed only one significant difference with growth of female at Point Leuseur significantly higher than at Livingstons (Table 9).

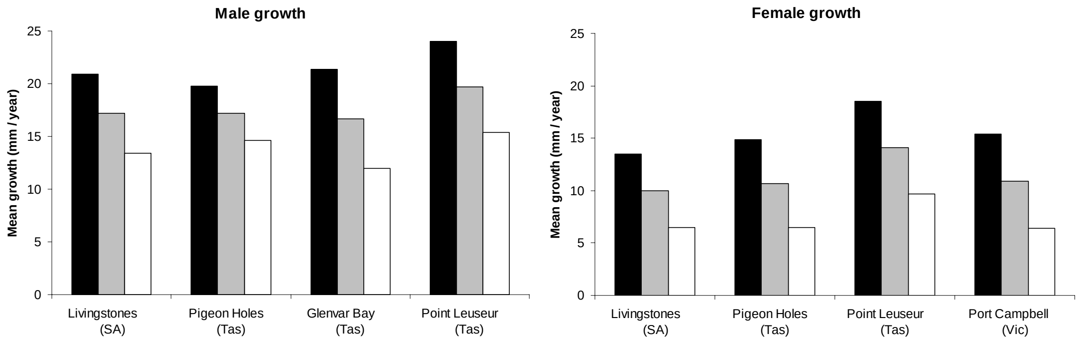

**Figure 27. Estimates of growth per year using the stochastic model for all sites with sufficient recaptures. Time at liberty >0.6 years. Black, grey and white bars represent growth at 50, 60 and 70 mm CL respectively.**

**Table 8. Comparison of growth between sites within Tasmania and South Australia using the stochastic model where reliable growth estimates were possible. Minimum time at liberty of 0.6 years.**

| State | Site comparison | Sample | n | Chi$^2$ | p |
|---|---|---|---|---|---|
| **Tasmania** | Pigeon Holes | Males | 69 | 2.229 | ns |
| | Point Leuseur | | 23 | | |
| | Pigeon Holes | Females | 104 | 43.112 | $p<0.05$ |
| | Point Leuseur | | 26 | | |
| **South Australia** | Livingstons #1-5 | Males | 50 | 3.05 | ns |
| | Livingstons #6 | | 48 | | |

**Table 9. Comparison of growth between sites in Tasmania, Victoria and South Australia using the stochastic model for minimum time at liberty of 0.6 years.**

| Site comparison | Sample | n | Chi$^2$ | P |
|---|---|---|---|---|
| Livingstons (SA) | Males | 35 | 0 | ns |
| Glenvar Bay (Tas) | | 24 | | |
| Livingstons (SA) | Males | 35 | 3.609 | ns |
| Pigeon Holes (Tas) | | 69 | | |
| Livingstons (SA) | Females | 26 | 1.496 | ns |
| Pigeon Holes (Tas) | | 104 | | |
| Livingstons (SA) | Males | 35 | 6.884 | ns |
| Point Leuseur (Tas) | | 23 | | |
| Livingstons (SA) | Females | 26 | 14.660 | $p<0.005$ |
| Point Leuseur (Tas) | | 26 | | |
| Port Campbell (Vic) | Females | 15 | 2.075 | ns |
| Livingstons (SA) | | 26 | | |
| Port Campbell (Vic) | Females | 15 | 2.053 | ns |
| Pigeon Holes (Tas) | | 104 | | |
| Port Campbell (Vic) | Females | 15 | 7.407 | ns |
| Point Leuseur (Tas) | | 26 | | |

### Density manipulations

As already shown, few significant differences in growth were found between the sites in this study, and none were found between the sites where density had been increased by translocating lobsters from adjacent areas. The density of the Pigeon Holes site was increased by 1,073 lobsters in addition to 1,488 resident lobsters. A very coarse estimate of the population numbers at Pigeon Holes can be derived by multiplying the recapture rate of 205 by the number of resident lobsters tagged, giving 7,440 (assuming no movement out of the study area). The addition of 1,073 lobsters to this estimate would represent a 14% increase in density. Similarly, at the South Australian Livingstons #5 site, 151 resident lobsters were tagged and the 9% recapture rate gives an estimate of 1,677 lobsters. In this case, the additional 249 recaptures would represent a 15% increase in density. From these very rough estimates, it is clear that growth rates were not changed significantly with a 15% increase in density.

## Discussion

This work has been successful in describing the juvenile growth of *J. edwardsii* in southeastern Australia.

An unexpected finding was the difference in growth found between males and females at such an early size. Growth rate of females has been shown to decrease after reaching sexual maturity (McGarvey et al. 1999, Annala and Bycroft 1988). This work shows that the growth is already differentiated between the sexes well before females show external signs of reaching sexual maturity. No growth differences were found between the sexes up to 40 mm CL (Chapter 3) but at 50 mm CL, males were growing 1.4 times faster than females. It is not surprising that the average moult increment for the smaller size range of juveniles was the same for both sexes. The differences in growth between males and females between 50 and 60 mm CL, prior to females becoming mature resulted from a higher frequency of moulting for males. Only once the females started to reach maturity did the moult increment begin to decline in comparison with the male moult increment. More significant was the reduction in the frequency of female moulting from approximately 3 – 4 moults each year to a single annual moult. In comparison, males continued to undertake between 3 –4 moults over all the range of size classes sampled. Some changes in female growth must be occurring between 40 and 50 mm CL, which corresponds to the time when juvenile *J. edwardsii* form social aggregations (Edmunds, 1995; Butler et al., 1999). Hooker et al. (1997) found significant higher growth for males in the $2^+$ size class, corresponding to 50-60 mm CL. As we measure maturity by external characteristics, there should be some time lag in assessing maturity – ie growth could be slowed by internal development of reproduction 1 or more moults before external features indicating maturity are apparent.

The growth transition matrices from this work will improve the current length structured models currently used in the fishery (Hobday and Punt 1999, Punt and Kennedy 1997) and should improve the ability to model and evaluate relationships between early juvenile, pre-recruit abundance and entry to the fishery.

The stochastic model provided a useful description of growth, however large numbers of recaptures could not be used because of short times at liberty between 0.3 and 0.5 years, in many cases the model would not run or provided poor estimates. This is due to the model assumption of constant growth, which is not applicable to crustaceans where for short times at liberty, length increments can vary considerably, depending on the timing of the recapture within the moult cycle. Estimates of growth at length decreased as the time at liberty was reduced in an analysis, so a consistent minimum time at liberty was required if growth estimates were to be compared between sites. Unfortunately the need to set a minimum time at liberty causes considerable data loss but is unavoidable when using this type of model and highlights the need for development of growth models better suited to crustaceans. The deterministic growth model developed by Francis (1998) was also used but did not perform as consistently as the stochastic method particularly with small sample sizes at short times at liberty.

The results of this work showed no overall difference between growth in each state. The fact that Point Leuseur (Tasmania) had the highest growth rate across the study sites in the three States was not expected. However, within Tasmania, the adult growth rate at Point Leuseur is intermediate between the slow growth areas in the south-west and the higher growth in the North (ref?). The South Australian sites were situated in the slowest growth rate area for that State (McGarvey et al. 1999) and the Victorian site in a slow-intermediate growth area (Hobday and Smith 2000).

Establishment of control sites for density enhancements in this type of study is difficult and the approach taken was to compare growth at enhanced sites with that at nearby sites. The low recapture rates from the individual South Australian sites meant these comparisons were not possible. In Tasmania, comparison of growth at Pigeon Holes (density enhanced) to the nearby Glenvar Bay site showed no significant difference for males and there were insufficient female recaptures for comparison. Densities of lobsters were probably not increased sufficiently in this study, but even if they had, movement off the study reefs (Chapter 8) may have still led to inconclusive results. It is not surprising therefore, that differences in growth were not found with the density manipulation experiments.

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# Chapter 5 - Design considerations for an artificial reef to research juvenile southern rock lobster

## Introduction

*In situ* research of juvenile rock lobsters is difficult due to the cryptic habitat they occupy. The need to evaluate survival and growth of early benthic phase lobsters has been hampered by lack of easy access to these animals from the wild. It is important to gain insights into the growth rates of newly settled lobsters and their survival. Survival estimates are also required to determine whether increased natural larval recruitment, re-seeding or enhancement would lead to improved recruitment to the fishery. Growth is addressed in chapters 3 & 4 and survival in chapters 6 &b 7 of this report.

Previous work exploring growth, movement and mortality of newly settled lobsters has centred around the tropical lobster *Panulirus argus* in Florida (Butler 1997). This species uses algae as the primary settlement habitat prior to moving into more complex reef habitat. Despite strong habitat selectivity by juvenile *P. argus*, recapture rates of microwire tagged individuals were typically between 2-4% (Butler pers comm.).

Because of the complexity of the habitat, previous work on *Jasus edwardsii* has focussed upon puerulus collectors, which monitor relative settlement rates, giving little insight into ecological and habitat requirements of recent settlers (Edmunds 1995). Studying newly settled *J. edwardsii* in a natural environment has proven particularly difficult due to their cryptic nature. Edmunds (1995) experienced low capture rates in the wild despite extensive diver searches of complex rocky reef habitat, and low recapture rates upon release of collector caught individuals.

To overcome the complex nature of natural reef environments, artificial reefs or regular substrates tend to make searching for juvenile lobsters easier. Norman and Yamakawa (1994) utilised regular holes in the vertical face of a mudstone reef to successfully study ecological and habitat requirements of juvenile *Panulirus japonicus.* Although some similar habitats have been found in Australia (eg Blackfellows Cave in South Australia and Pt Campbell in Victoria) these are not readily accessible and restricted to only a few sites over a narrow geographic range. A more flexible option was to create artificial reefs that were both searchable and also provided suitable shelter. To reduce the likelihood of emigration, and therefore increase recaptures from the artificial reefs, the artificial reefs were placed over sand rather than reef.

## Methods

### Pilot studies

Prior to the construction of the artificial reefs, a series of pilot studies were conducted to determine a suitable design for settling puerulus. This involved selecting a construction material, and shaping it to maximise shelter availability for lobsters of varying sizes.

A series of collectors were designed to test shelter preference. Six collectors were constructed from Hebel blocks (CSR constructions; www.hebelaustralia.com.au), and six from natural limestone blocks. Limestone was sourced from Mt Gambier in South Australia where it is the most common inshore reef substrate and is known puerulus settlement habitat in this region. These materials were easy to sculpt, relatively lightweight, and in the case of the limestone a known lobster shelter substrate. The 200 x 200 x 600mm blocks were mounted horizontally approximately 800mm above a cement base on a steel pole. Each collector had a number of 'lobster shelters' sculpted into it (Figure 28). These were categorised as small (12mm), medium (16mm) and large (25mm) holes, as well as small (25mm wide) and large (60mm wide) crevices. The holes were uniformly 60mm deep, while the crevices were 250mm long and 60-80mm deep. The collectors were deployed in a circular pattern at Bicheno, on Tasmania's east coast.

**Figure 28. Hebel collector. Puerulus settled upon collectors of this design constructed of Hebel in preference to limestone.**

Collectors were surveyed at month intervals from July 2000 to February 2001 and from July 2001 to September 2001. During each survey, all juveniles were removed after noting which hole or crevice they were occupying. The stage of the puerulus (3 stages) and post-puerulus (1 stage) were recorded as per standard puerulus classifications (Booth 1979), and the animals released onto nearby reefs. Although there are 3 puerulus stages, these refer to changes in physiology and colour and there is no moult between stages and no increase in size.

## Design and Construction of Artificial Reefs

### Tasmania

Utilising the information on substrate and hole / crevice selectivity resulting from the pilot studies, 6 artificial reefs were designed and constructed in Tasmania. Design constraints included a maximum size which could be handled on land, and then safely deployed and recovered from research vessels. In addition, the reefs had to be sturdy enough to withstand ocean swells.

The Tasmanian artificial reefs are 2.40m x 1.20m x 0.21m in size. They were constructed by layering Hebel blocks (CSR construction) above and below a layer of cement 7cm thick. A steel frame was attached both above and below to provide support, and four smaller blocks are attached to the top frame. The whole reef was then attached to four cement filled tyres located at the corners of the reef, which act to anchor the reef securely to the sea floor (Figure 29).

The resultant artificial habitats therefore had 6 faces in the horizontal plane and 16 faces in the vertical plane. Into each of these faces was drilled a variety of 'lobster shelters'. These were categorised as small (16mm), medium (25mm) and large (45mm) holes, as well as small (25mm wide) and large (60mm wide) crevices. The holes were uniformly 60mm deep, while the crevices were 250mm long and 60-80mm deep. The 'lobster shelters' were apportioned so each size class of habitat provided a similar surface area. This resulted in fewer crevices than larger holes, and fewer larger holes than smaller holes.

In Tasmania 6 artificial reefs were deployed in pairs at three locations, these being Pigeon Holes , Pot Bay (Chapter 1, Figure 1) and Bicheno (north east coast). They were lowered into position by a deck-mounted crane from a research vessel, and subsequently checked for damage and location by a diver. Four of the reefs were on sandy substrate while the other two reefs were deployed over reef, on the east coast near Bicheno. All reefs were deployed in between 6-12m of water, and the positions marked by GPS for further reference.

## Victoria and South Australia

Based upon the successful Tasmanian design, further artificial reefs were built and deployed in South Australia and Victoria. These sites had an additional constraint of no large research vessel to deploy the artificial reefs. This resulted in altering the design so that reefs could be deployed from smaller vessels. These reefs were constructed from the same materials and offered exactly the same choice and availability of habitat, however the artificial reefs were built in a modular fashion so no individual section was too large to deploy from a small craft, and be handled into position by a diver.

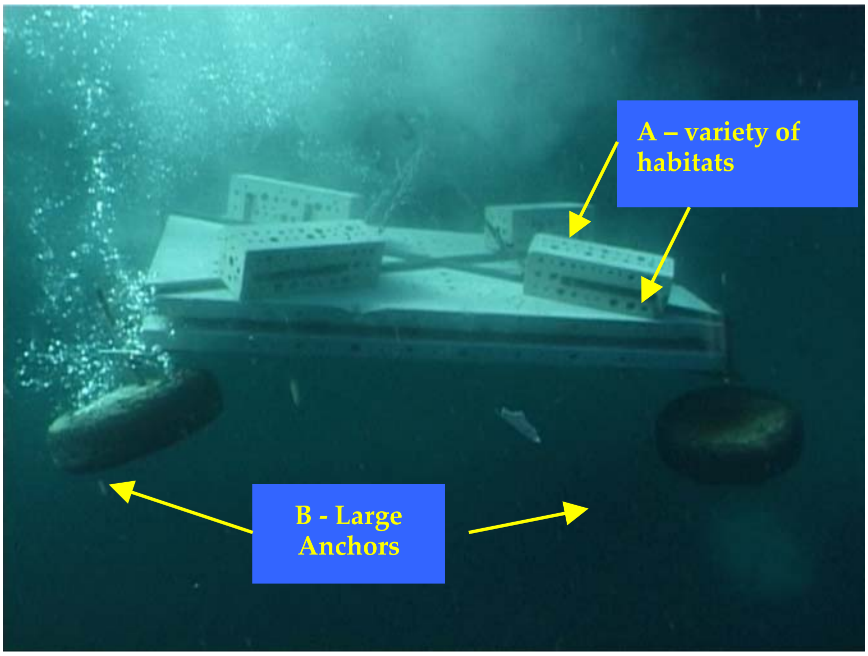

**Figure 29. Artificial reef showing A- a variety of habitats and B-Large anchors.**

## Survey and sample design in Tasmania

After being deployed the artificial reefs were left in situ for approximately three months to ‘condition’, prior to any puerulus being released. This conditioning period allowed a range of fish, algae and invertebrates that occur on adjacent natural reefs to colonise the artificial reef and therefore assist in mimicking a natural habitat.

Puerulus were sourced from existing puerulus monitoring projects (Gardner et al., 2001) within each State. Prior to release upon the artificial reefs, puerulus were microwire tagged with individually coded micro-wire tags using the NorthWest Marine Technology’s handheld multishot tag injector (NorthWest Marine Technology, Inc., Shaw Island, Washington) and then held overnight in a 100 litre container of oxygenated ambient seawater. The following morning healthy animals were selected from the container and tested with the ‘tagging wand’ (NorthWest Marine Technology, Inc., Shaw Island, Washington) to ensure tag retention. As the puerulus supply was opportunistic and the period of this study coincided with the lowest settlement period recorded since inception of the monitoring program in 1992, numbers tagged and subsequently released varied considerably between months.

Prior to the addition of any puerulus to the reefs, a diver surveyed the reef for existing puerulus/juveniles, and the position on the reef, the face (horizontal or vertical) and the sized shelter which the animal had selected were recorded. The tagged animals were then released by hand into a haphazard selection of shelter sizes, making sure to distribute the animals across the artificial reef. The position of the animals being released was also recorded by diver.

At each subsequent survey this process was repeated, thereby building up a matrix of positions inhabited by puerulus and juveniles. Survey and release dates were variable to coincide with the opportunistic supply of puerulus, however surveys and release events generally occurred monthly between August and February, with no surveys occurring between February and August.

Due to the limited number of puerulus that were available to be added to the reefs, sampling from the reefs was reduced to approximately six monthly intervals. During each sampling period divers would record the numbers and position of all the animals on the artificial reefs, and then harvest approximately half of the animals from the reef for dissection and tag recovery. Divers selected by eye the larger animals and removed them by hand, thereby keeping the animal intact for measurement and subsequent tag recovery. At the conclusion of the project, the artificial reefs were wrapped in a large sieve bag and recovered to the deck of a research vessel for dismantling and thorough searching for any individuals that had previously been overlooked. In total there were five periods of recovery of tagged animals.

## Survey and sample design in Victoria and South Australia

The intention was to replicate the sampling and survey methodologies used in Tasmania at both the other sites where the reefs were located, however both these sites had unforseen problems, and were unable to be utilised to their full capacity.

The modified design used at these sites to allow smaller modular artificial reefs to be deployed was found to be insufficiently robust to withstand the extremes of weather prevalent on the exposed South Australian coast, and consequently the reefs were quite badly broken in a large swell.

In Victoria, the artificial reefs were deployed in a more sheltered location. However high current movements in the area caused higher than anticipated levels of sand movement, and a number of the holes and crevices became silted up thereby reducing the available choice of habitat for the puerulus released onto these reefs. In addition, Victoria had limited opportunity to access wild caught puerulus, so animals released onto the Victorian reefs were caught and tagged in Tasmania, then posted in an insulated, oxygen rich environment to Victoria for release onto the reefs. Because of the siltation, the habitat preference information from this site has been excluded from the analysis. Due to delays in construction of the reefs and long periods of unsuitable weather for deployment of the reefs, the time between puerulus addition and final harvest was only 3 weeks.

## Statistical Methods

### Pilot Studies - Comparison between substrates and shelter size

A two way factorial ANOVA was used to test the effect of substrate type (Hebel and limestone) and hole size on catches of puerulus. Data were restricted to months where puerulus were captured on both substrates to eliminate zeros from the data set that otherwise led to violation of the assumptions of homogeneity of variance and normality. For this analysis, months were treated as replicate samples so that the analysis was conducted for data collected over seven months. The significance between different categories of hole size were subsequently analysed by Tukeys HSD.

The effect of hole size was also examined in the artificial reefs with catch data pooled across all samples and different sites treated as replicates. Analysis was by ANOVA.

### Artificial reefs - Orientation of shelter

The effect of the orientation of shelter (on the vertical or horizontal face) was examined in the artificial reefs with catch data pooled across all samples and different sites treated as replicates. Data was standardised by dividing vertical counts by 2.81 to account for the larger number of holes on vertical faces of each reef (372 vs 132). Analysis was by a Wilcoxon non-parameteric test rather than ANOVA as assumption of normality was violated by the high incidence of low counts on horizontal faces.

# Results

## Pilot Studies - Comparison between substrates and shelter size and type

The interaction term between substrate type and hole size was found to be non-significant and the analysis was repeated on the reduced model for the two factors of substrate and hole size.

There was a significant difference in the number of puerulus that settled on the different collectors ($P = 0.065$) with an average 30% more puerulus settling and remaining on collectors made from Hebel compared to limestone (Figure 30). As Hebel is widely available, and is known to be uniform in structure and easy to sculpt, it was selected as the material from which to construct the artificial reefs.

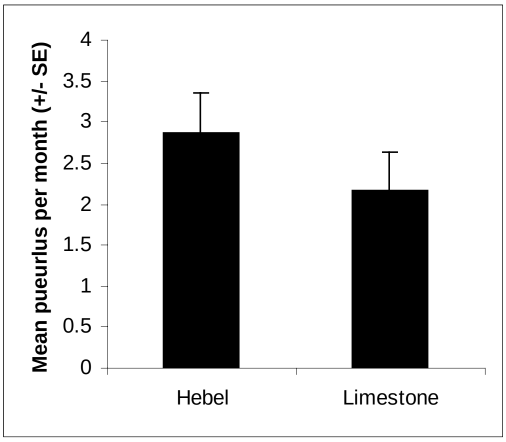

**Figure 30.** **Natural puerulus settlement patterns on collectors made of Hebel and Limestone. Hebel caught or retained animals significantly better than Limestone.**

Significantly more puerulus and post-puerulus lobsters were found in medium holes than any other hole or crevice (Figure 31, P = 0.025). Lobsters were found in all the available habitats although holes were preferred to crevices with 86 % of lobsters found in holes. Small holes and large crevices where the least preferred habitat with on only 5.5% and 3.7% of lobsters found in these respectively. No puerulus were found in the large crevices and no post-puerulus were found in the smallest hole.

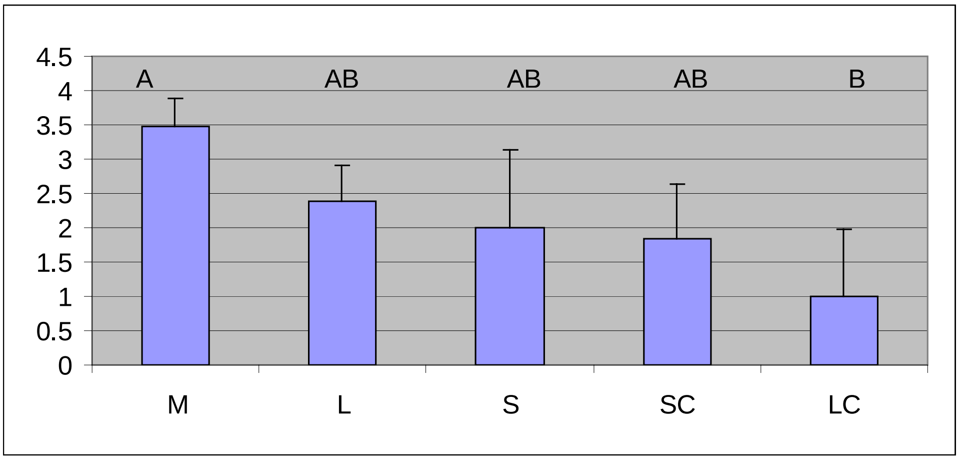

**Figure 31.** **Comparison of the mean number of puerulus/month and post puerulus/month that utilised 16 mm (M), 24 mm (L) and 12 mm (S) diameter holes, small crevices (SC) and large crevices (LC) per month.**

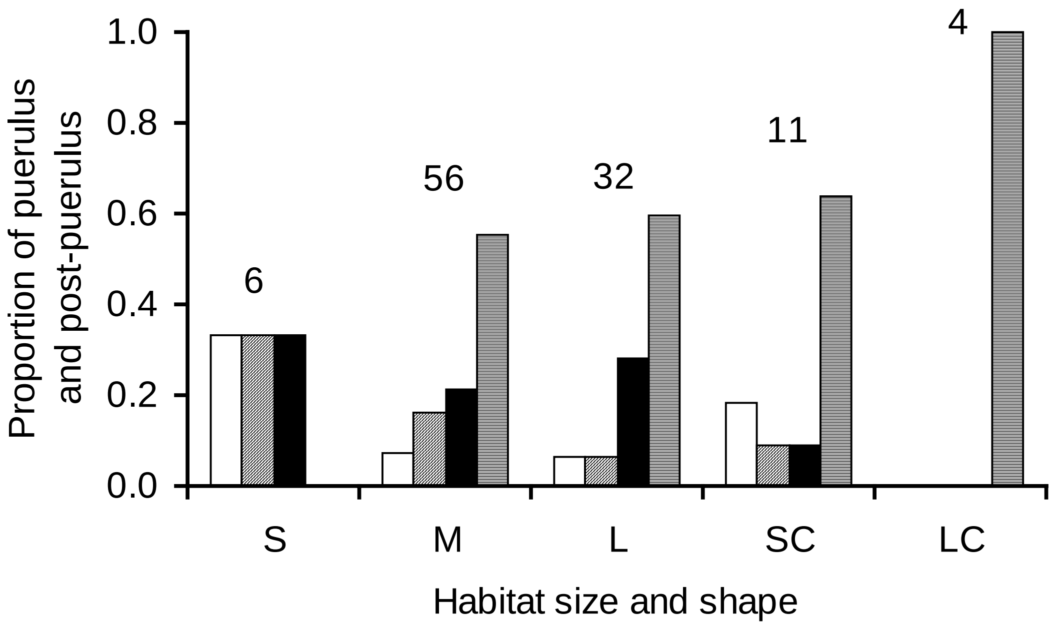

Figure 32. **Graphed is the proportion of lobsters occupying each shelter type on the collectors that were stage 1 (open bar), stage 2 (oblique hatched bar) or stage 3 pueruli (solid bar) or post-pueruli (horizontal hatched bar). The total numbers of lobsters that occupied each shelter type is indicated above each set of bars. The shelter types are the same as indicated in Figure 31.**

In general, as the lobsters moulted from puerulus to post-puerulus they sought larger habitats, irrespective of whether they were holes or crevices (Figure 32). Although 56% of the lobsters found were post-puerulus, the majority in each stage was found in medium holes (Figure 33). There was a substantial increase in the proportion of stage 3 lobsters using the largest hole size compared to the earlier puerulus stages. This suggests that the stage 3 puerulus were shifting to larger holes in preparation for their moult to post-puerulus.

This information was utilised in the design of the artificial reefs where the minimum hole size was 16mm, and 45mm diameter holes were added in an attempt to retain larger animals to the reef. Only one style of crevice was used on the artificial reefs. The crevice was wider than the larger crevice at the opening (to accommodate larger post-puerulus) and tapered to a small crevice width at the rear of the crevice.

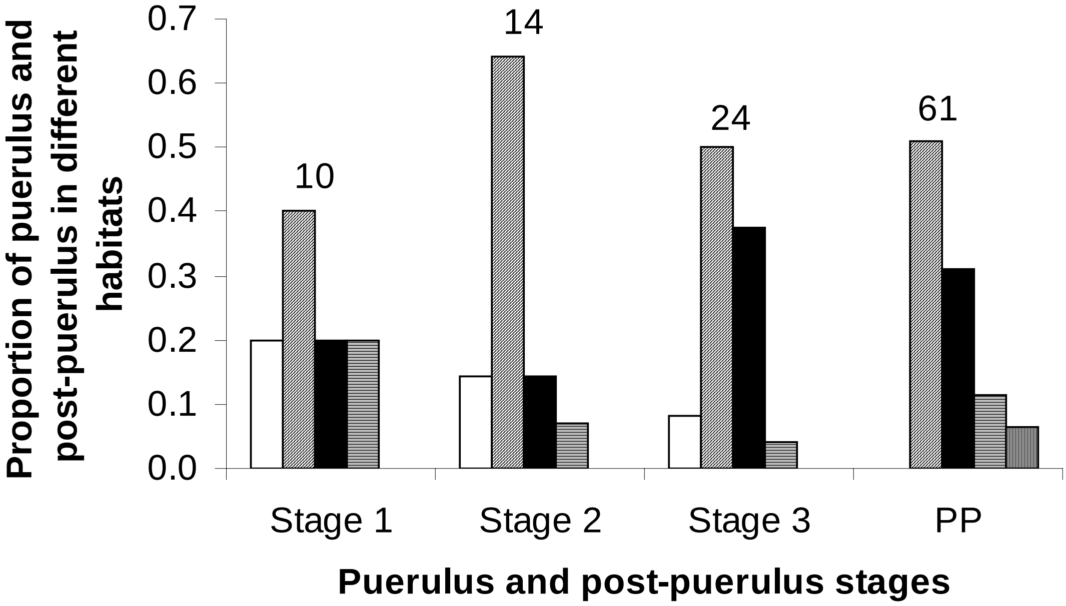

Figure 33. Comparison of the proportion of different puerulus and post-puerulus (PP) stages that used the different habitats. (12 mm (open bar), 16 mm (oblique hatched bar), 24 mm (closed bar), small crevice (horizontal bar) and large crevice (vertical bar). Number of puerulus in each stage is recorded above the respective stage).

## Shelter preference in artificial reefs

Significant effect of orientation of face was detected with 96% of juveniles resighted on vertical faces (P=0.006). Divers noted that silt build-up was greatest in horizontal holes, which may have contributed to the observed pattern.

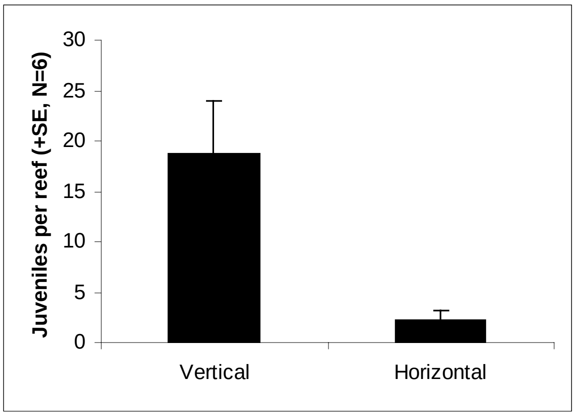

Figure 34. Comparison of the number of juveniles found in holes and crevices on the vertical and horizontal surfaces of the artificial reefs. No effect of position of shelter in relation to current or exposure was detected (P=0.55, N=6).

Although the tagged puerulus were being released onto the artificial reefs rather than settling naturally, the pattern of shelter use on the artificial reefs was similar to the patterns seen on the collectors although no significant difference was found between habitat types.

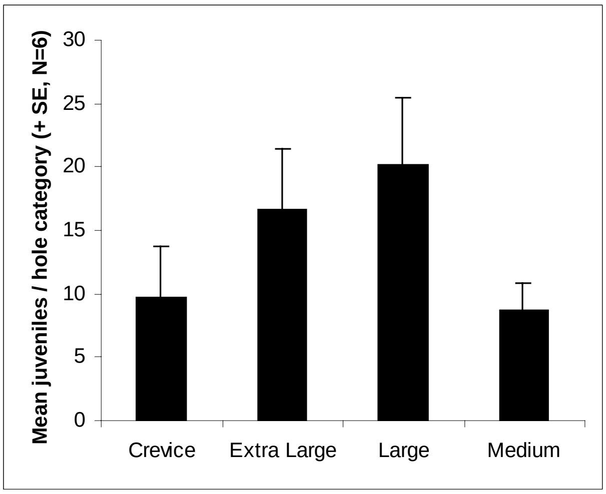

**Figure 35. Comparison of the mean number of juveniles observed in each of the shelter types on the artificial reefs. Error bars are one standard error.**

## Comparison between artificial reefs

The total number of lobster observed on the artificial reefs was greatest at the two sites in the Derwent Estuary with very few lobsters being sighted on the artificial reefs at Bicheno (Figure 36). Artificial reefs were located on reef at Bicheno compared to sand for the two sites in the Derwent Estuary. Both Pot Bay and Bicheno artificial reefs are adjacent to puerulus monitoring sites that use "Booth" collectors for routine monitoring of puerulus settlement. Differences in the number of puerulus available for settlement on the artificial reefs is unlikely to account for the difference between sites as Bicheno had 3.8 and 15.5 times more settlement than the Derwent Estuary in 2003 and 2004 respectively (Figure 37). Numbers observed on the reefs at Bicheno did not increase during the periods of peak puerulus settlement as they did in the Derwent Estuary (Figure 38). This suggests that the artificial reefs placed on natural reef did not retain settled puerulus. This could be due to either increased predation or emigration from the reef.

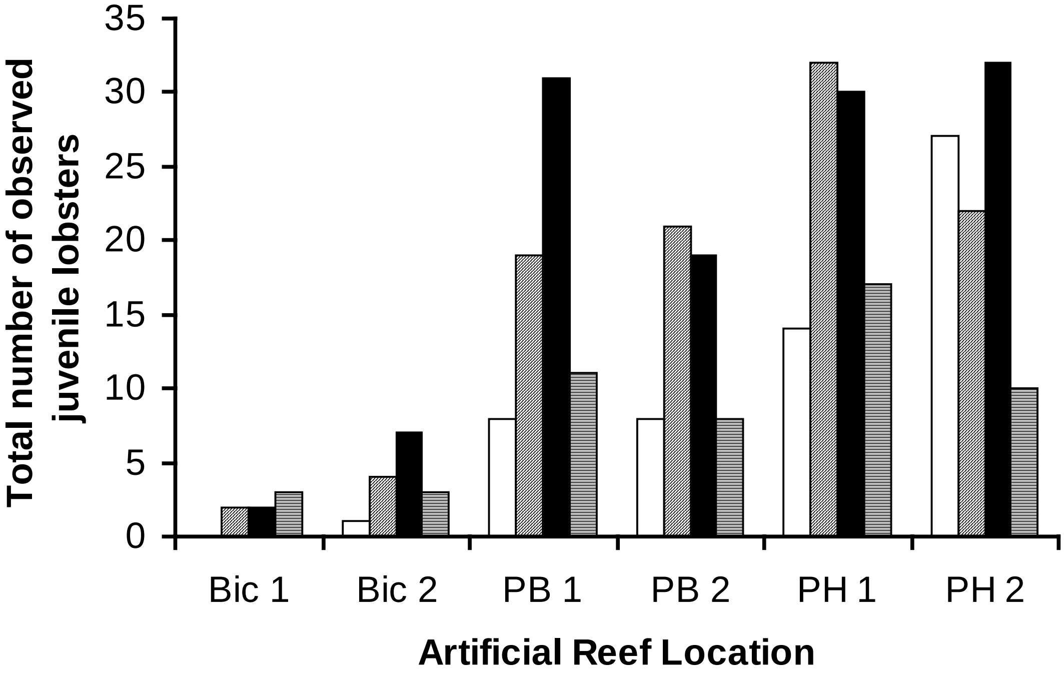

**Figure 36.** Comparison of the total number of juveniles sighted in medium (16 mm, open bar), large (24 mm, oblique hatched bar) and extra large (45 mm, solid bar) holes and crevices (horizontal bar) at the six artificial reefs (Bic = Bicheno, PB = Pot Bay and PH – Pigeon Holes)

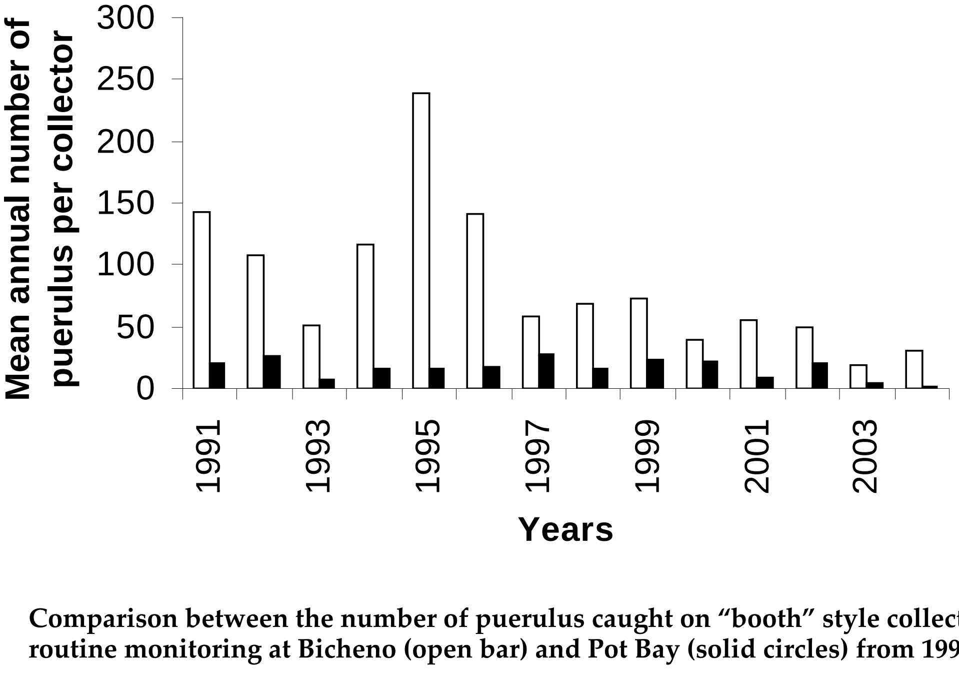

**Figure 37.** Comparison between the number of puerulus caught on "booth" style collectors during routine monitoring at Bicheno (open bar) and Pot Bay (solid circles) from 1991 to 2004.

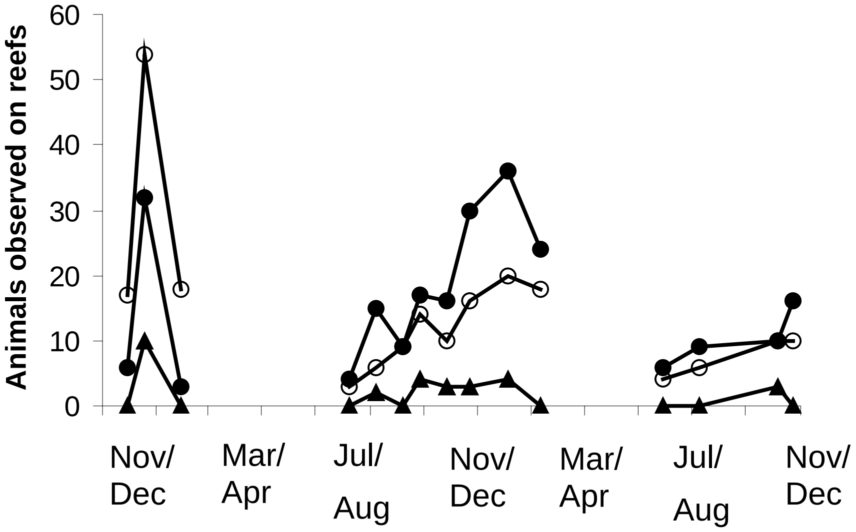

**Figure 38. Total number of lobsters observed at Bicheno (solid triangles), Pot Bay (open circles) and Pigeon Holes (solid circles). Numbers are the aggregate of both replicates.**

### Qualitative observations between reefs

Divers observed that the artificial reefs in the Derwent Estuary were degrading faster than those exposed to the more oceanic conditions at Bicheno. On retrieval of the artificial reefs for their final disassembly prior to intensive checking for lobsters, it was noted that the four reefs in the Derwent Estuary had been substantially bored by a boring mollusc (*Barnea* sp) that was not present at the Bicheno site.

The growth of algae on the artificial reefs was substantially faster on the Bicheno reefs than the reefs in the Derwent River. The species of algae, fish and invertebrates that were present in, on and around the artificial reefs were consistent with those described by Edgar and Barrett (1997) for this region.

## Discussion

The use of artificial reefs to obtain life history information on animals brings with it the biases associated with the differences between natural and artificial habitats. However, in cases where gaps in our knowledge are lacking due to the inability of obtaining sufficient samples from complex habitats, artificial reefs offer insights that can begin to redress this knowledge gap. This is the case for *Jasus edwardsii* where the newly settled puerulus and early benthic stage (up to 12 months or 40 mm CL) dwell in complex reef systems that contain substantial areas that can not be surveyed or searched without breaking the reef apart.

To obtain growth and survival estimates of newly settled puerulus we wanted to create an artificial structure that would mimic the natural reef habitat, provide appropriate shelter for the puerulus and be easily searched.

Although many man-made products can leach byproducts that are either toxic or unnatural, the Hebel used in this study out performed the natural substrate. Furthermore, the high settlement recorded shortly after deployment of the artificial reefs suggest that conditioning of the substrate was not a prior requirement for settlement (Figure 38). The rapid decline in observed puerulus on the reef in the following month would suggest that the reef was not able to support this settlement over the longer period. In contrast, settlement from August to February in the middle of the survey and July to December at the end of the survey showed continued increases in the number of juvenile lobsters found on the reef, although the peak number during these periods was less than observed on the artificial reefs shortly after deployment. There was no decline in the number of lobsters caught from each tagging event which further suggests that conditioning enhanced the probability of lobsters remaining on the artificial reefs (Figure 39). With the exception of one tagging event in July 2004, the probability of recapturing a lobster was generally less than 20%.

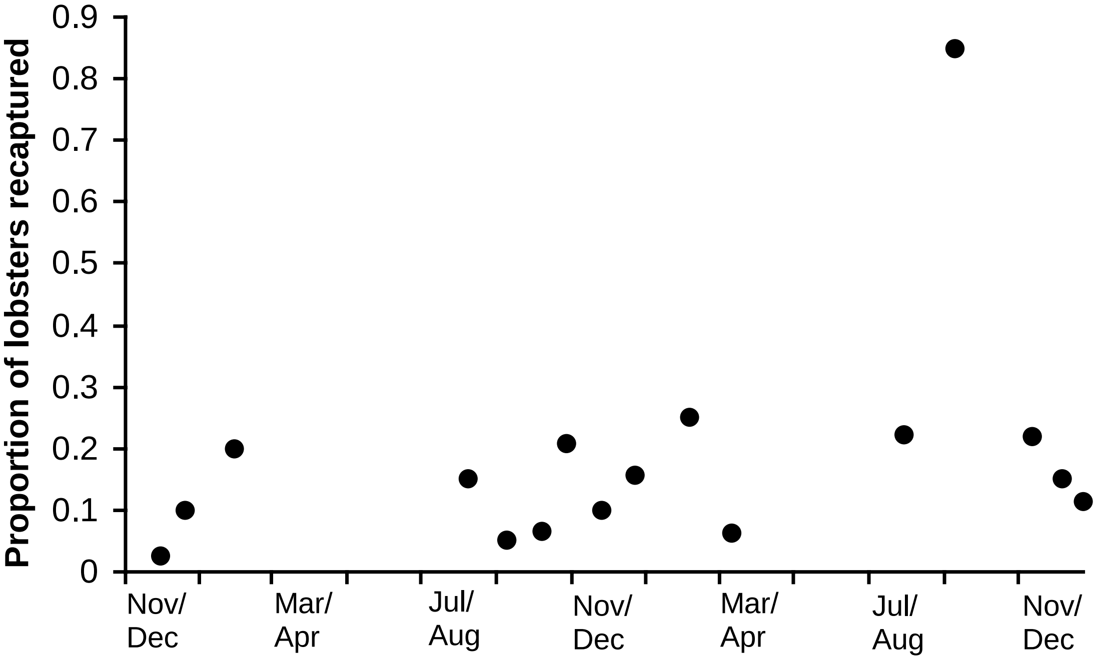

**Figure 39. Proportion of lobsters recaptured from each tagging event.**

Our study supported the work of Edmunds (1995) and Norman et al., (1994) who found *J.edwardsii* and *Panulirus japonicus* respectively to utilise holes only slightly larger than their diameter. A supply of different sized holes was important as the puerulus began to move into larger holes in preparation for moulting and then into larger holes as they grew. In addition to the holes and crevices, the orientation is also important when considering reef habitat.

The lack of settlement and retention of post-puerulus and juveniles on the artificial reef at Bicheno was surprising given the high settlement rates that occur in this region. Towards the end of the project, when the artificial reef was covered in algae to the extent that it was difficult to find by divers, there was still no improvement in settlement on the artificial reef. The lack of settlement could be associated with the placement of the artificial reef on top of the reef structure and thus puerulus may have settled on the reef crest and thus be 'filtered out' prior to finding the artificial reef. The poor retention of added tagged puerulus would suggest that these puerulus either preferred the natural reef (emigration) or were more susceptible to reef associated predators while on the artificial reef. All reefs were observed to have a range of predators of lobsters and divers found that the macro flora and fauna similar to adjacent natural reefs.

The more rapid decay of the reefs in the Derwent Estuary indicates that there were substantial differences between the two sites. Norman et al., 1994 found *P.japonicus* to utilise residual holes of Pholad burrowing bivalves and considered that any artificial reef would need to be able to mimic these holes. However, other organisms such as oysters also blocked these holes and thus continual replacement of holes was necessary. The Hebel offered a substrate that was permeable for Pholads to utilise but a considerable thickness would be required to ensure that the integrity of any structure remained viable over time.

These results demonstrate that artificial reefs made of Hebel are suitable man-made structures that can be used to study juvenile lobsters that are normally inaccessible. Careful design into these structures is warranted if the design is to maximise habitat. With the increased global interest in the use of artificial reefs to study fish behaviour, enhance fish stocks and provide sanctuaries, these results are the first to attempt to mimic lobster habitat in Australia. We believe that they offer considerable potential to understand the behaviour and dynamics of an important life history phase of rock lobster that is considered the most vulnerable of the benthic life history phase.

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# Chapter 6 -Estimating the survival of early benthic stage juveniles

## Introduction

Survival of early benthic juveniles is an aspect of the biology lobsters about which little is known. Improved information on survival would be valuable for both applied fisheries management and also for better understanding of the broader ecological processes that influence lobster populations. An example of an applied need for information on puerulus survival is for the harvest of puerulus for aquaculture. Estimates of the survival of puerulus in the first year post-settlement affected the permit conditions of these operations and ultimately their economic viability (Gardner et al., in press).

Information on survival of early benthic stages is also relevant to the prediction of future catches from puerulus settlement. This is because it is necessary to know both the time required to recruit to the fishery (See Chapter 4 – $0^+$ juvenile growth rate) and whether bottlenecks in survival affect the relationship between puerulus settlement and recruitment to the fishery. Any bottlenecks would limit the ability to predict future catches from puerulus catch rates.

Estimating survival for this first year post-settlement is extremely challenging and has not been attempted previously for *Jasus edwardsii*. This challenge is due to the difficulty in locating early benthic juveniles on natural reef, which make it virtually impossible to locate animals for both tagging and subsequent recapture. Settling puerulus seek out individual holes in the reef structure and remain solitary until they reach a size of approximately 35 – 45 mm CL (Edmunds, 1995). If research were conducted on natural reef, such extended hours of diving would be required to source sufficient juveniles that the exercise would be logistically and financially unviable. The problem would be compounded if surveys were repeated in several locations. Clearly a more logistically feasible option was required and we evaluated the potential for artificial reefs to be used in this type of research. The benefit of an artificial reef is that it can be readily searched due to known habitat (i.e. placement of holes and crevices) and can be dismantled to check for all juveniles. The development of reefs for this purpose is described in more detail in Chapter 5.

Determining the survival of animals in natural environments is typically done by mark-recapture studies, however this is difficult with juvenile lobsters due to their small size. Puerulus and early benthic juveniles have previously been successfully marked using individually coded microwire tags (Edmunds, 1995, Sharp et al., 2000). Multiple mark recapture analysis is a robust methodology for estimating survival (Brownie et al., 1985) and has been applied successfully for larger lobsters (Frusher and Hoenig, 2001). The use of microwire tags requires special consideration in the application of these models because the removal of the tag to read the individual code requires sacrificing the animal. Thus reading the tag number is type of mortality that must be accounted for in the survival estimate. Research surveys where early benthic juveniles are removed to permit tag identification are analogous to harvest events and can be analysed similar to fisheries models (Frusher and Hoenig, 2001).

This section evaluates the use of artificial reefs with microwire tagging technology and mark recapture analysis to provide estimates of survival. The combined methods are applied to the early benthic post-settlement stage of the southern rock lobster, *Jasus edwardsii*, where survival estimates from the wild have not been possible.

## Methods

### Artificial reefs

Details of artificial reef construction, placement and servicing are provided in Chapter 5.

## Collection and tagging of lobsters

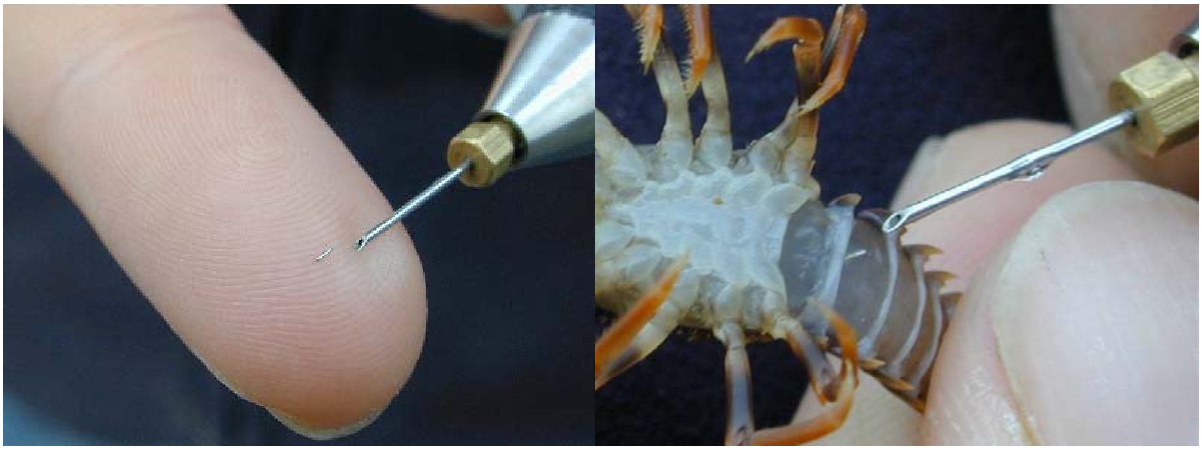

**Figure 40. The small size of individual coded wire tags (left) and coded wire tag is injected into a post-puerulus lobster (right).**

Lobsters were collected as pueruli from collectors deployed in eastern and southeastern Tasmania as part of an ongoing project to monitor rates of puerulus settlement (Gardner et al. 2001). Puerulus were tagged using Nortwest Marine Technology's binary coded wire tagging system (Figure 40). Tags are small enough that pueruli can be effectively tagged with minimal tag-induced mortality.

## Survival estimation

Survival estimation and model selection methods used here follow those outlined by Burnham & Anderson (1998). The model selection approach seeks to produce the best possible estimates of population parameters by identifying a biologically meaningful maximum-likelihood based model that best explains variability in the data, while excluding parameters that cannot be justified by the data. Akaike's Information Criteria (AIC) is used to select the most parsimonious model. Of a set of models, the most parsimonious model is the one that adequately describes the variability in the data with the minimum number of parameters (Burnham and Anderson, 1998). Parsimony was assessed using the quasilikelihood adjusted form of AIC (QAICc), incorporating an adjustment (variance inflation factor, $\hat{c}$ ) for minor lack of fit of the saturated model (Burnham et al., 1995; Anderson et al., 1998). If removal of parameters of interest for a particular hypothesis resulted in a decrease in QAICc, the hypothesis was accepted, and the reduced model was taken as the best general model against which further comparisons would be made (Burnham et al., 1995; Burnham and Anderson, 1998). While this method of model selection does not allow significance values to be attributed to tests between models, normalised QAICc weights provide a relative weight of evidence for a particular model best describing the data (Burnham and Anderson, 1998).

Recovery forms of data, where tag information is only available when an animal is removed from the population, are analysed using Brownie type models (after Brownie et al. 1985). Brownie models are structured to provide a measure of total survival ($S$) and 'harvest' mortality ($f$) (an alternative parameterisation allows for estimation of tag recovery rates). For the present study we are interested in mortality other than that related to 'harvest', as our harvest is the removal of lobsters for tag identification. This requirement is analogous to calculating natural mortality from fishery-based Brownie models, and is calculated simply as:

$$\text{Natural survival} = 1\text{-}S\text{-}f$$

Tagging experiments on artificial reefs were set up with the dual aims of assessing growth (see Chapter 4) and post-settlement survival of lobster puerlui and juveniles. This, combined with the sporadic availability of pueruli due to settlement variability, meant that the timing of release and resighting events was not ideal for mark-recapture analysis. The effect of experimental constraints is to limit the number of models that can be fitted to the data. The low number of recapture events relative to the number of releases dictated that it was not possible to obtain time-dependent estimates for mortality, which must instead be estimated as a single parameter for the entirety of the study. While this limited the ability to determine variation in survival between months or years, the main objectives of the study were to evaluate methods to estimate survival rates of early benthic lobsters in addition to providing estimates of survival.

Harvest mortality ($f$) could be constrained to zero on occasions where no recapture surveys were conducted, and time-dependent estimates of $f$ obtained for the remaining periods. Additionally, we know that $f$ for the final capture occasion = 1, as all lobsters were harvested by bagging the reef and pulling it apart out of the water (see Chapter 5). The resulting most general model considering these constraints can be represented as:

$$S_{1\text{-}18}(.)S_{19}(0)f_{\text{survey}}(t)f_{\text{no survey}}(0)f_{19}(1)$$

That is, survival for sampling periods 1-18 (subscripts) is estimated as a single parameter (.), and survival for period 19 (the final period) is constrained to zero. Harvest mortality was allowed to vary over time for periods when surveys were conducted, was constrained to zero where no surveys were conducted, and was constrained to 1 for the final harvest. Seven parameters are estimated under this model (a single $S$ parameter and seven $f$ parameters, one for each of the recovery occasions except the last).

The structured nature of this model leaves little room for proposing alternative hypotheses. A single alternative tested was that harvest mortality did not vary significantly over time, represented as:

$$S_{1\text{-}18}(.)S_{19}(0)f_{\text{survey}}(.)f_{\text{no survey}}(0)f_{19}(1)$$

Two parameters ($S$ and $f$) are estimated under this model.

# Results

## Recapture surveys

Of the 500 tagged pueruli released onto the 4 artificial reefs in the Derwent Estuary, 79 were recaptured (16%). The highest number of lobsters captured during a single survey was 21, and this was achieved during the final 2 surveys where the intent was to collect all lobsters seen, rather than selecting the largest juveniles (see Chapter 5).

None of the 229 tagged pueruli released onto the 2 artificial reefs at Bicheno, Eastern Tasmania, were recovered, although 29 post-pueruli were sighted on the reef. These were all small, recently released or settled lobsters, and were not recovered in the hope of obtaining growth data over a longer period. All analyses presented here relate to artificial reefs in the Derwent Estuary only.

## Goodness-of-fit testing

Prior to model fitting, goodness-of-fit (GOF) testing is required to test that the most general model in the *a-prior* set fits the data. Testing followed the bootstrapping procedures implemented in program MARK (White and Burnham 1999). While this method has drawbacks (see White 2002), it offers maximum flexibility for testing the fit of non-standard models. Model fit is usually tested on the most general model possible - in this case $S(t)f(t)$, however this is clearly inappropriate here given the sampling design. Since there were many occasions during the trial where no lobsters were released, we would not expect a model with full time-dependent estimates for sampling mortality to fit the data.

Despite the flexibility of the bootstrapping GOF test, we were still unable to fully accommodate the model design for this project. It is not possible to test the fit of models with 'fixed' parameters, yet a model without $f$ constrained to zero where no sampling was undertaken is clearly not appropriate. The closest model we were able to test can be represented as:

$$S_{1\text{-}18}(.)S_{19}f_{\text{survey}}(t)f_{\text{no survey}}(.)$$

That is, apparent survival for occasions 1 – 18 (subscripts) is estimated as a single parameter, while the final occasions (subscript 19) where the reef was bagged and removed is estimated independently. Survey-induced mortality ($f$) for each sampling occasions where pueruli were collected is estimated independently, while occasions where no sampling occurred where grouped. While this is not ideal, it is reassuring that the model estimate of survival for the final period when we attempted to catch (sacrifice) every lobster was extremely low (0.001).

Using the bootstrapping method, estimates of the over-dispersion parameter, $\hat{c}$, can be derived either by dividing the observed model deviance by the mean deviance from the bootstrap simulations, or by doing the same calculation for model estimates of $c$ ($c = \chi^2/\text{df}$). While these methods tend to produce similar results, there is no consensus in the literature as to which of these approaches is preferred. In the present study results were markedly different, with $\hat{c} = 1.6$ calculated using $c$, and $\hat{c} = 3.0$ using model deviances. As it is generally considered that model fit is adequate if $\hat{c} \leq 3.0$ (Lebreton et al 1992) we can conclude that as the data fits this less-than-ideal model, fit is likely to be adequate for a model that better allows for experimental design. As well as providing a measure of model fit, $\hat{c}$ is incorporated into error estimation for model parameters , For the purposes of this analysis, the more conservative estimate ($\hat{c} = 3.0$) was used.

## Survival estimation

Of the two models tested, the first, with time dependent estimates for harvest mortality, was most strongly supported by the data – there was no measurable support (QAICc weight = 0.000) for the alternative model, suggesting that significant differences exist between harvest rates from separate survey occasions. Annual survival (*S*), which accounts for both harvest mortality and natural mortality was estimated as 0.15±0.06. Estimates of harvest mortality ranged from 0.017±0.02 (September 2003) to 0.15±0.04 (January 2005) (Figure 41 A). Resulting natural survival estimates (excluding harvest mortality) ranged from 0.16±0.07 (September 2003) to 0.30±0.09 (January 2005) (Figure 41 B). Average annual survival calculated from the six estimates for survival was 0.23±0.08.

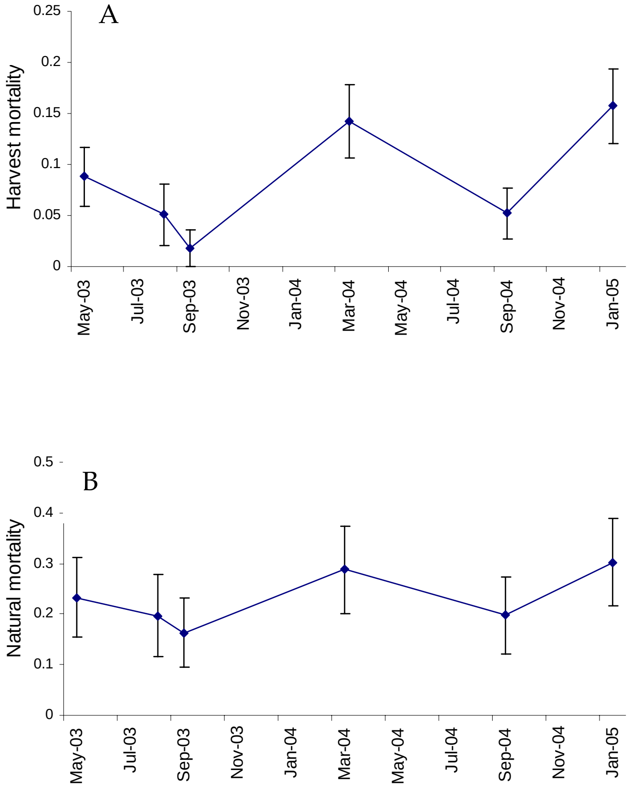

**Figure 41. Estimated annual harvest mortality (A) and natural survival (B) for puerulus released onto artificial reefs in the Derwent Estuary**

# Discussion

This project is the first time that larger-scale artificial reefs, that have been manipulated to create early benthic juvenile habitat, have been used to obtain estimates of survival for early benthic juvenile lobsters. Artificial reefs are required for tracing the fate of tagged post-puerulus as the probability of being able to either find puerulus for tagging and release, or releasing tagged puerulus onto natural reefs and then finding them again was considered extremely low. Habitat for *Jasus edwardsii* is very complex and consists of dense algal cover and crevices and caves that cannot be searched (i.e. behind large boulders or deep and narrow cracks in limestone walls).

Natural settlement on all the artificial reefs during this project suggests that puerulus initially find the reefs suitable. The lack of resighted juveniles on the artificial reefs placed on natural reefs compared to those placed on sand suggest that either the settled puerulus 'prefer' the natural reef or that predators, associated with the natural reef were able to prey on these more exposed animals. Although beyond the scope of this three-year project, longer conditioning of the reefs could have resulted in a more natural community. The small number of recapture surveys meant that we were unable to model temporal variability in survival, and hence could not detect if survival increased as the experiment progressed. Survival estimates during this study were also compromised by the extremely low settlement that occurred on our standard collectors. These collectors were the source of puerulus to be added to the artificial reefs and the low settlement rates resulted in adjustments to the original design. The range of hypotheses that could be tested through the survival modelling process was restricted by the low numbers, and relatively few recapture occasions. Despite the low number of puerulus added to the artificial reefs and the irregular timing of additions, we were still able to obtain an estimate of overall annual survival from the altered design.

Our estimate of annual survival from the Derwent Estuary site is considerably higher than previous estimates for *J. edwardsii* (Edmunds, 1995), *Panulirus cygnus* (Phillips et al. 2003) and *Panulirus argus* (Forcucci et al 1994; Hernkind and Butler, 1994). The previous study on *J.edwardsii* by Edmunds (1995) also used coded wire tagging and mark-recapture analysis to estimate survival. In that study small 'house' bricks with large oblong holes that transversed the brick were the artificial substrate. In Edmunds (1995) experiment, both the time at large was short (maximum = 77 days) and the number of recaptures small (N=36). Survival/site retention estimates from his study were extremely low, with an estimated annualised maximum of 0.03%. Survival estimates for post-puerulus of tropical lobster (*P. argus*) range from about 3% per annum, measured by correlating puerulus settlement with juvenile abundance (Hernkind and Butler 1994) to 6.8% per annum (Forcucci et al. 1994), measured by mark-recapture experiments. A key difference between these two studies is that the former covers a period from free-swimming puerulus, through the process of settlement. As with the present study, the latter only covers the post settlement period. Mortality of pueruli associated with approaching, and searching for shelter in the predator-rich reef environment may be considerable and is not included in the calculations for these studies.

The region where artificial reefs were placed in the Derwent Estuary is notable for its consistently high abundances of juvenile lobsters (Gardner et al. 2000). However, based on extensive trials with puerulus collectors placed around the Tasmanian coast, we would not expect this comparatively sheltered area to receive high rates of puerulus settlement. A possible explanation is that puerulus survival in this area is unusually high. Further evidence for site differences comes from the Bicheno site that was sampled in this study. No recaptures were obtained from that site despite similar number of releases to the Derwent Estuary site, which implies a rate of survival that approaches zero.

The extent to which artificial reefs are dissimilar to natural reefs and therefore provide biased results is unknown. Survival may have been enhanced on the artificial reef through a lack of predation pressure. While common predators of juvenile *J. edwardsii* (Oliver et al., 2005) were observed by divers on the artificial reefs, the density and diversity may have been lower than on natural reef. As the artificial reefs in the Derwent Estuary were on sand, the chance of reef-associated predators encountering the artificial reef may have been low. A difference in the quality of available habitat may also contribute to the high survival rate. In a study to determine the preferred hole size to use in the design of the artificial reefs, early benthic lobsters showed a marked preference for holes only slightly larger than their body size and moved to larger holes as their body size increased. (see Chapter 5). The comparative rarity of these ideal holes in natural reef would result in early benthic juveniles selecting larger or irregular holes and crevices. These shelters may make it more difficult for juveniles to avoid predation.

Further studies on the extent of any bias in survival estimates from artificial reefs would be of value. If actual survival of early benthic *J. edwardsii* were similar to published estimates for other species, then the artificial reefs would have enhanced survival by 8 to 10 fold. If survival from one year post settlement to recruitment to the fishery was equivalent irrespective of number of puerulus available (i.e. no density dependent processes), then the artificial habitat would have resulted in an 8 to 10 fold increase in fishery yield per puerulus settling onto the reef.

Experimental design is often compromised when working in the natural environment. To overcome the shortfalls experienced during this project we suggest that future experiments focus on collecting animals from monthly collections and holding these in captivity until the required number has been achieved prior to addition to the artificial reefs. Mills et al. (2004) demonstrated that animals returned to the wild after being held in captivity for up to 12 months behaved and survived similarly to natural settlers.

While the artificial reefs are not perfect approximations of natural reef, they provided a mechanism for gaining insights into a previously unknown component of the lobster's life history. Prior to this study, we were unsure that sufficient post-pueruli could be recaptured in such an experiment to provide meaningful survival estimates. Alteration of the artificial reefs to more closely mimic natural reefs (e.g. distribution, size and shape of holes, cracks and crevices) can be used to determine habitat quality, and thus help identify potential regions in southern Australia that are poor puerulus and early benthic juvenile habitat and therefore limit recruitment to the fishery.

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# Chapter 7 - Estimating spatial variation in natural survival of juveniles

## Introduction

Natural mortality (*M*) is one of the more critical parameters for stock assessment modelling of rock lobsters yet information derived from field studies is typically scarce. Population models from South Australia, Tasmania, Victoria and New Zealand include natural mortality at an estimated value of 0.1 year$^{-1}$ although this consistency is more a function of lack of information than any spatial consistency in *M* . The actual data used to derive these estimates was a small number (<100) of tag recaptures in the case of Punt and Kennedy (1997) and Breen and Kendrick (1994). More recent work by Breen and Kendrick (1999) and Starr et al. (1999) developed posterior distributions for *M* for stocks of *J. edwardsii* in New Zealand but these estimates were neither size specific nor consistent. The posteriors obtained by Breen and Kendrick (1999) emphasize values higher than 0.1 year$^{-1}$ while those obtained by Starr et al. (1999) emphasize values lower than 0.1 year$^{-1}$. As with these other assessment models, Hobday and Punt (2001) noted that the Victorian model was unable to account for changes in *M* with increasing size of the lobsters. This effect of size on *M* can be critical for population modelling and Lorenzen (2005) has argued that research is required to address this need. The research presented here attempted to fill this knowledge gap for *Jasus edwardsii* by quantifying *M* of animals smaller than those sampled in traditional t-bar tagging projects. That is, for lobsters less than 80 mm but also larger than the first year post-settlement (which is is dealt with separately in Chapter 6).

An important conceptual issue for stock assessment and lobster management is the effect of density on survival. Density dependent mortality clearly exists for all populations but is not included in assessment models for lobster stocks across southern Australia. This is a reasonable assumption for periods of a few years because lobster populations tend to be stable over this duration. However, large changes in density can occur over longer periods, such as by depletion through fishing or stock rebuilding by conservative management. A process of stock rebuilding is occurring in each of the southern States of Australia and the impacts of this on longer-term population dynamics are of interest for management planning. There is some expectation that settlement will be increased as stocks rebuild because declines in undersize abundance have been reported between the 1960's and the 1990's (Frusher et al., 2003). A critical question for stock management then becomes to what extent will increased settlement lead to increased productivity and opportunity for expanded harvests? Lorenzen (2005) noted that density dependent mortality of juveniles tended to dampen fluctuations in recruitment that may result from increased egg production.

Field experiments on the effects of density have been conducted for juveniles of some species of *Panulirus* in order to gain an understanding of density dependent processes. In juvenile *Panulirus argus,* these have indicated the presence of bottlenecks in survival through interactions between lobster size and shelter availability, predation risk and lobster density (eg Eggleston and Lipcius, 1992; Eggleston et al., 1992). This type of information would be of great value for *J. edwardsii* but is difficult to obtain due to difficulty of fieldwork on temperate rocky reefs. Recent advances in modelling techniques have increased the power and flexibility of analyses of tag recapture so that more can be made from smaller data sets (Mills et al., 2005). This has provided additional capability to address issues of density dependent processes in temperate species from rocky reef, which previously have received little attention.

The approach taken here to examine density dependent mortality was similar to that of Ford et al. (1988) where the density of juvenile lobsters on natural reef was manipulated. The effect of these removals on survival was examined by analysis of mark-recapture data.

## Methods

### Sampling sites and program

As described in Chapter 1.

## Data analyses

Resighting histories from dive surveys were analysed using Cormack-Jolly-Seber (CJS) mark-recapture models (Cormack, 1964; Jolly, 1965; Seber, 1965) modified to permit the inclusion of co-variates. We followed model selection and parameter estimation protocols outlined by Burnham and Anderson (1998). Methods are similar to those used to estimate the survival of newly settled post-pueruli in Chapter 6. This approach seeks to identify a biologically meaningful maximum-likelihood model that best explains variability in the data, while excluding parameters that cannot be justified by the data.

Apparent survival was modelled with carapace length as a covariate. For each site, two size/survival functions were produced. The bounds of these functions were defined from length frequencies of lobsters initially captured by divers at each site. We considered that the 'inflection point' on length/frequency graphs provided a measure of retention of lobsters of varying sizes at a given site. For lobsters represented by each size/survival function, a two-group survival estimate without the size covariate was also produced. To maximise the chance of having sufficient data for the two-group models, each group represented half of the lobsters within the dataset. Accordingly, sizes of lobsters represented by the groups varies within and between sites. Despite this, for one site (Pt Leuseur) we were unable to fit a two-group model for the smaller lobster due to insufficient data.

Models were selected through an iterative process of pairwise comparisons between the parsimony of a general starting model, and that of related but simplified models from the candidate set. The candidate set was chosen *a priori* to test biologically and experimentally feasible hypotheses relating to factors affecting survival estimates (Lebreton et al., 1992). Parsimony was assessed using the quasi-likelihood adjusted form of the Akaike Information Criteria ($QAIC_c$), incorporating where necessary the variance inflaton factor ($\hat{c}$) to allow for minor overdispersion in the data (Burnham et al., 1995; Anderson et al., 1998). The variance inflation factor adjusts for overdispersion in the data by reducing the sensitivity of the model selection process to fine scale detail within the data. If the $QAIC_c$ of the simplified model was lower than that of the starting model, the simplified model was adopted as the best general model against which further comparisons would be made (Burnham et al., 1995; Burnham and Anderson, 1998).

Goodness of fit (GOF) testing is required prior to the model reduction process to ensure that the most general model of the candidate set adequately fits the data – if this condition is not met, models with fewer parameters, and hence less capacity to explain variability in the data, will not fit. However, there are no direct methods of testing the fit of models which include covariates. The recommended approach (White and Burnham, 1999) is to test the most general model without including covariates. In this case, the most general model can be expressed as:

$$\Phi(t)\varrho(t)$$

That is, apparent survival ($\Phi$) is dependent on time (t), as is resighting probability ($\varrho$). Clearly, if the co-variate is significant in describing the variation in the data, introducing the co-variate in the model can only improve model fit. Accordingly, applying a variance inflation factor calculated without including the co-variate is a conservative approach.

The primary aims of this analysis were to obtain an annual estimate of juvenile survival, and to elucidate any changes in apparent survival with lobster size. Accordingly, we fitted the model $\Phi(.)\varrho(t)$, providing a single annual estimate for apparent survival but allowing for time dependent estimates of resighting probability. The latter is appropriate as search effort was not constant between surveys, and environmental conditions (eg water clarity) and seasonal differences in lobster behaviour may affect the probability of divers resighting lobsters. We then tested whether apparent survival and resighting probability were influenced by lobster size by comparing the above model with models including lobster carapace length as a covariate for apparent survival and resighting. All models were initially structured using the identity design matrix and logit link function, as this provided meaningful estimates for the greatest number of parameters.

A limitation of mark-recapture models relying wholly on tag resighting data is that survival estimates (referred to as 'apparent' survival) are confounded by any event other than predation that leads to a tag becoming permanently unavailable for resighting. In our case the most likely events of this nature are permanent emigration of tagged individuals from the study area and tag loss. These factors will all act to reduce apparent survival estimates, so in the absence of independent measures of movement and tag loss, apparent survival estimates produced here must be taken as minimum estimate.

The effect of damage on survival was assessed at the Pigeon Holes site. New damage was often caused by divers in the process of capturing juvenile lobsters and was a potential bias of results. Old damage was separated from new damage by the presence of melanization over the wound. Each lobster was given a total damage score where any scored item of new damage was given a value of one, such that a lobster with damage to two left legs, a right antennae and carapace would have a damage score of five. Old damage was given half the value of new damage and added to the total. Any lobster with a damage score of 3 or less was coded as low damage, while greater than 3 was coded as high damage. Data were analysed using a 2 state model, with damage code as state, allowing for transitions between states at any stage. The application of this model approach appeared reasonable in that damage was random across time and GOF tests were passed.

# Results

## Effect of damage

The incorporation of damage did not improve model parsimony for fits to the Pigeon Holes data set. Results were re-analysed with reverse transitions between states disallowed, thus making the biological assumption that a lobster with high damage at any stage remained compromised (reduced growth rate etc). This approach still resulted in no detectable effect. Damage codes were then reassigned so that scores above six were coded as high damage, which also resulted in no detectable effect. Further division of the damage information into more than two damage states was not possible as individual cell counts were reduced below acceptable levels for model fits. Given these outcomes, the effect of damage was not considered in subsequent analyses of survival.

## Pigeon Holes (Enhancement Site)

The most parsimonious model for Pigeon Holes included time and size dependence for both survival and resighting probability. Based on the AICc values, this model received seven times more support, as did the next best model, in which apparent survival was not dependent on size. Models without carapace length as a co-variate for survival or resighting probability had no detectable support from the data.

The observed relationship between apparent survival and carapace length (Figure 42) was contrary to the expected pattern of increasing survival with time and consistent across size groups. The effect of size on apparent survival is consistent across groups and is contrary to what was expected, that is, survival appears to decline with increasing size rather than increase.

Two possible causes for the observed trend are that a size-dependent survival bottleneck exists at the site, or that rates of movement increase as lobsters increase in size. These explanations are not mutually exclusive, for instance a size-dependent habitat bottleneck may be expected to lead to increased movement away from the site by larger lobsters

The sample design at Pigeon Holes was intended to enable the effect of movement to be separated from survival as with research by Mills et al. (2005). However, the number of recaptured lobsters were insufficient to estimate movement rates by a multistate model (that is, goodness of fit testing failed).

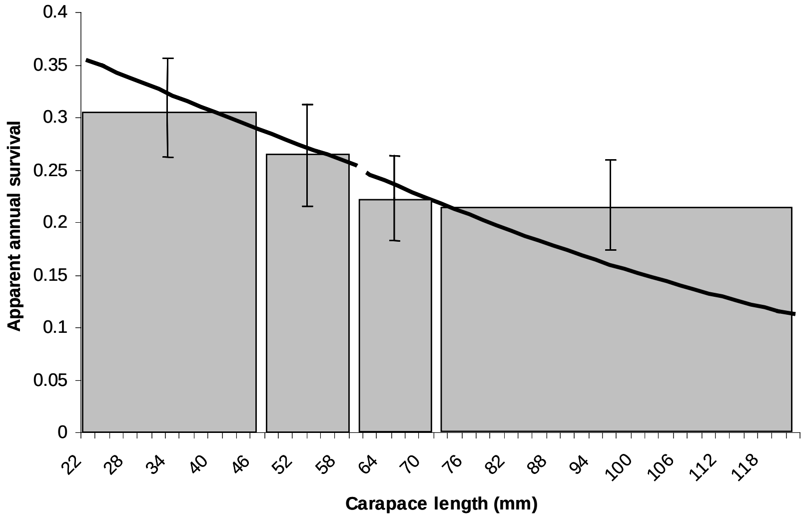

**Figure 42. Apparent survival/size functions for juvenile lobsters at the Pigeon Holes site. Survival in relation to size is modelled by treating size as a covariate (two linear functions) and separately for each of four different size categories (+/- 95% confidence limits).**

## Glenvar Bay (Donor Site)

As with the 'enhancement' site at Pigeon Holes, the effect of juvenile size (CL) on survival was significant at Glenvar Bay. However, the pattern of the effect of size was quite different to that of Pigeon Holes with an initial increase in apparent survival with increasing size, followed by a decrease in apparent survival with size for lobsters over 65 mm CL (Figure 43). The observed pattern in apparent survival for smaller lobsters (<65 mm CL) at Glenvar Bay is consistent with the expected pattern of increasing survival with size. As lobsters become larger at this site, it appears that rates of movement increase (Chapter 8) so that apparent survival declines.

The most parsimonious model from Glenvar Bay included time-dependent apparent survival estimates. Comparisons of this model for Pigeon Holes and Glenvar Bay are shown in Figure 44. A trend of decreasing apparent survival at Pigeon Holes relative to that at Glenvar Bay can be clearly seen. This trend is consistent with an effect of altered survival in response to altered density at the two sites.

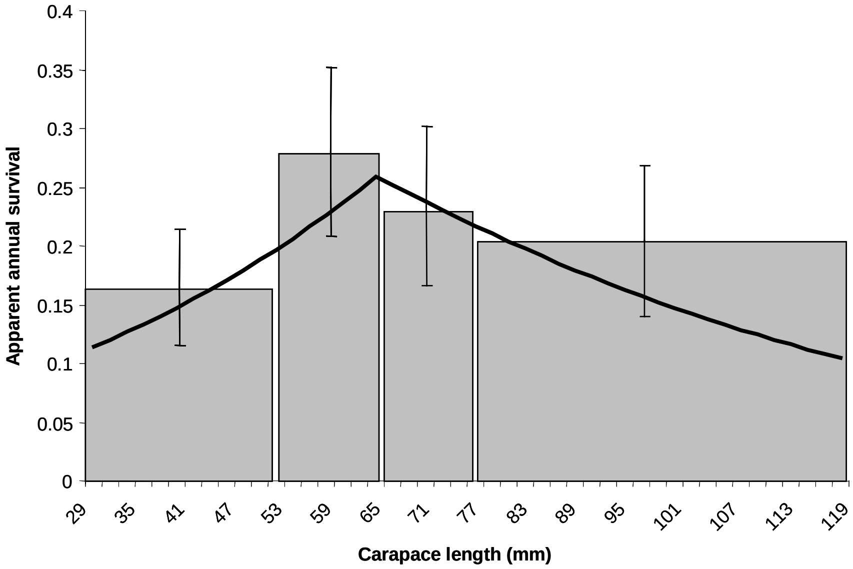

**Figure 43.** Apparent survival/size functions for juvenile lobsters at the Glenvar Bay site. Survival in relation to size is modelled by treating size as a covariate (two linear functions) and separately for each of four different size categories (+/- 95% confidence limits).

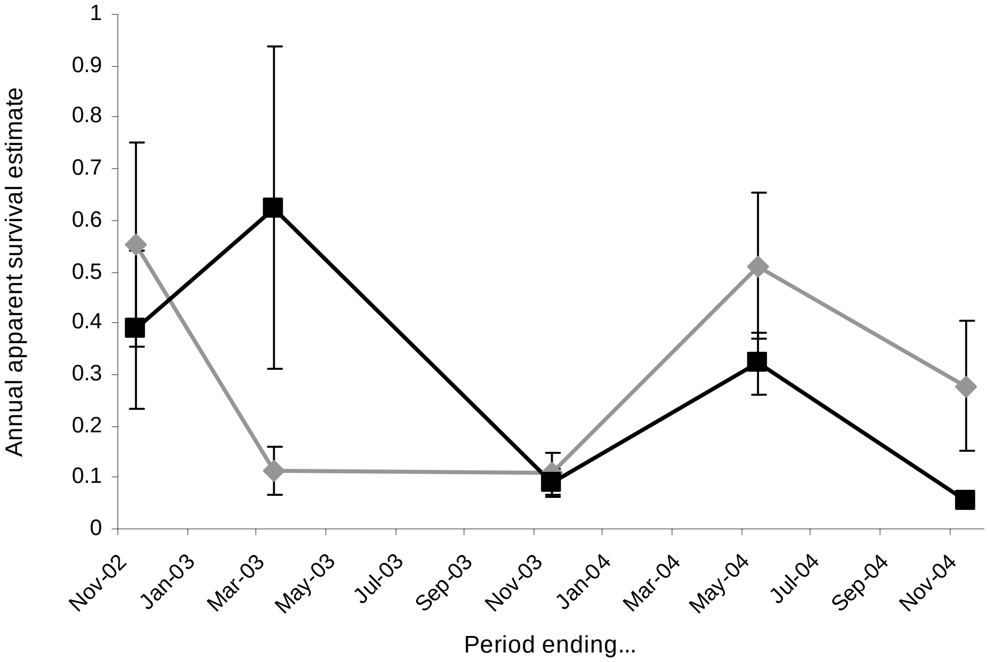

**Figure 44.** Time dependent apparent survival estimates for Pigeon Holes (black) and Glenvar Bay (grey) with all sizes pooled (+/- 95% confidence limits).

## Pt. Leuseur (Maria Island) and Livingstons

Densities at Pt. Leuseur (Maria Island) and Livingstons were not manipulated. Model fits to data from Pt. Leuseur (Maria Island) supported the inclusion of size as a covariate with a similar pattern to that of Glenvar Bay: increasing apparent survival with size initially followed by decline in apparent survival with size for larger lobsters (Figure 45). Livingstons exhibited a different pattern to other sites with little effect of size on apparent survival, and consistently low levels of apparent survival across all sizes (Figure 46).

Three of the four sites had similar survival estimates for the smallest size group that were tagged. The exception was Pigeon Holes, which had very high estimated survival for smallest stages.

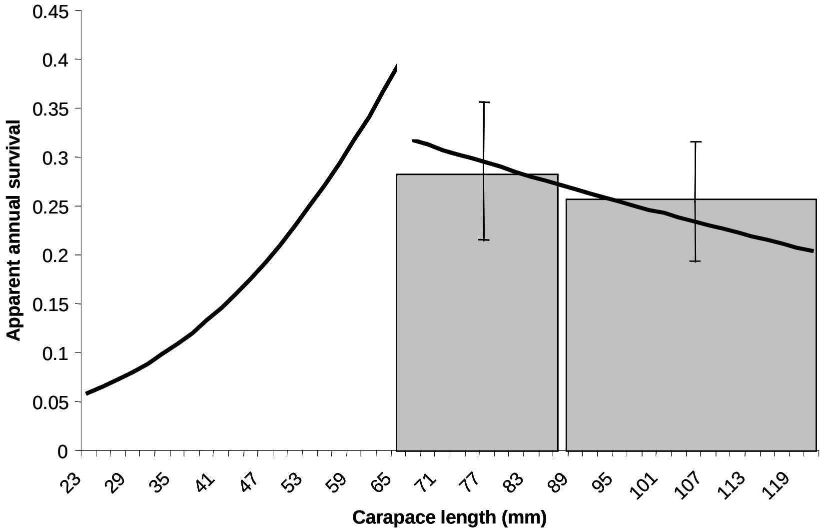

**Figure 45. Apparent survival/size functions for juvenile lobsters at the Pt. Leuseur (Maria Island) site. Survival in relation to size is modelled by treating size as a covariate (two linear functions) and separately for each of two different size categories in the upper size range. There were insufficient recaptures for a categorical analysis of lobsters below 65 mm CL (+/- 95% confidence limits).**

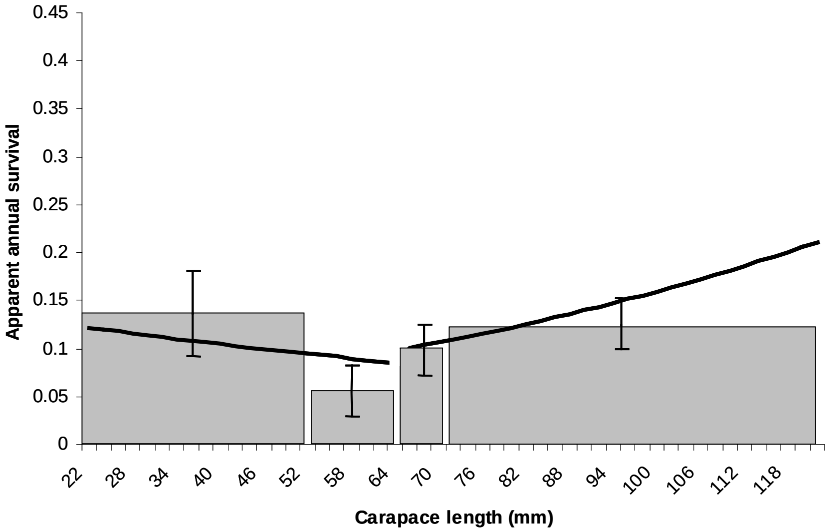

**Figure 46.** **Apparent survival/size functions for juvenile lobsters at the Livingstons site. Survival in relation to size is modelled by treating size as a covariate (two linear functions) and separately for each of four different size categories (+/- 95% confidence limits).**

## Discussion

This study has provided estimates of survival for juvenile *Jasus edwardsii* between 30 and 80 mm CL. While there appeared considerable variation between sites, some patterns were apparent. Both Pt. Leuseur (Maria Island) and Glenvar Bay followed the expected pattern of increases in survival with increasing size for sizes less than around 65 mm CL.

Survival rates of smaller juveniles less than 45 mm CL were around 15-20% per annum for the Glenvar Bay and Livingstons sites, and higher again at Pigeon Holes at around 30%. This is much greater than has been reported from mark-recapture studies of similar sized *Panulirus argus*. Forcucci et al. (1994) estimated monthly survival of only 51%, which equates to annual survival of much less than 1% (although we acknowledge that annualisation is not biologically appropriate because growth beyond the 45 mm CL category is so rapid in that species). Higher rates of survival were observed by Bannister et al. (1994) for another temperate species, *Homarus gammarus* with survival from early benthic phase to 85 mm CL of between 50% and 84%.

Importantly, the size structure of lobsters from Pt. Leuseur and Glenvar Bay appeared more typical of fished regions with larger legal sized lobsters represented. In contrast, samples from Pigeon Holes and Livingstons included few larger lobsters.

Spatial differences in survival of smaller lobsters sampled in this study were similar to those observed for microwire tagged juveniles that had recently settled (Chapter 6). Survival of juveniles in the first year after settlement at Pigeon Holes was estimated at around 23%, which is considerably higher than field-based estimates from other species. Survival of small juveniles tagged for this component was also very high at Pigeon Holes with estimated mean apparent survival of over 30% for juveniles less than 45 mm CL. Pigeon Holes appears to have characteristics that promote excellent survival for juvenile lobsters. These characteristics may include low competition for resources due to relatively low settlement as indicated by low puerulus catches from the adjacent monitoring site at Iron Pot, South Arm (Chapter 8). This site also has a relatively high supply of nutrients because flows from the Derwent River tend to sweep this shore of the Derwent Estuary (Leeming and Nichols, 1998). An additional possibility is that recreational angling may remove many of the predators from this site. This site is adjacent to an urban area and recreational anglers were active within 100 m of the site on many of the days that sampling was conducted.

The apparent decline in survival of lobsters with increasing size at most sites suggests lobsters are either moving or dying more frequently as they become larger. These two options may both be contributing to our observed pattern of declining survival with increasing size. This pattern suggests some limitation at these sites for larger lobsters, such as insufficient food or shelter. It is interesting that survival in relation to size appears to shift at around 65 mm CL, by which size juvenile *Jasus edwardsii* form social aggregations (Edmunds, 1995; Butler et al., 1999). This ontogenetic shift in behavioural and shelter is thought to confer a protective advantage on individuals but may not have be possible at the inshore sites sampled here due to the micro-structure of the reef.

Shelter limitation is a form of bottleneck and would act to reduce the opportunity for expanded harvests with increased levels of recruitment at that specific site. Alternatively, these reefs may act as feeder reefs for adjacent populations and thus increased recruitment could result in increased supply of juveniles to adjacent habitats.

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# Chapter 8 - Juvenile size frequency, movement and spatial patterns

## Introduction

Movement patterns of the southern rock lobster *Jasus edwardsii* have been the focus of considerable research in recent years, having particular relevance for management as well as implications for marine protected areas (MPAs) (Gardner et al. 2003; Kelly & MacDiarmid 2003). Across its range, movement of southern rock lobster is typically migrational and appears closely linked to reproductive, moulting, and feeding cycles. In New Zealand, aggregations of lobsters on offshore sites are highly seasonal and directional movement to these areas appears strongly correlated to the timing of these events (McKoy 1983; Annala & Bycroft 1993; Kelly et al. 1999; Kelly 2001). Specifically, aggregations of male lobsters peak offshore at times of elevated feeding rates in July (after mating), whereas ovigerous female numbers are highest in August before larval release in September/October.

In Australia, evidence of mass directional migration by *J. edwardsii* has not been largely evident to date. An initial tagging study in the Cape Jaffa region of South Australia in the 1970s revealed that recaptured lobsters had moved relatively short distances (<5 km) and exhibited strong site fidelity (Lewis 1981). A small proportion of animals, however, did exhibit long distance directional migration (up to 28 km) from inshore to offshore sites in the Cape Jaffa region. A more recent study confirmed these findings with 68% of 14,280 recaptures being < 1 km from the initial release site (Linnane et al., 2005). Similarly, a study of 39,000 tag-recapture events in sites around Tasmania between 1973 and 2001 indicated that in most areas, more than 90% of animals moved <5 km (Gardner et al. 2003).

In areas where significant movement by *J. edwardsii* has been observed, rates of movement are highest in immature individuals. In South Australia, immature females were observed to migrate from a lobster sanctuary to offshore reefs >100 km away (Linnane et al., 2005). Directional movement by immature females has also been observed in Tasmania's northwest (Pearn 1994) and Victoria (Hobday and Flint, 1998). The aim of this study was to investigate the movement patterns of *J. edwardsii* in relation to juvenile sex and size frequency in sites across South Australia, Victoria and Tasmania.

## Methods

### Sites and sampling protocol

Details of experimental sites and sampling protocols are described in Chapter 1 of this report. This section deals with size frequency and movement results from tagged juveniles at Livingstons Bay in South Australia and Pigeon Holes and Glenvar Bay in Tasmania. Recapture rates at all other sites were too low to enable robust analyses. Broadly, a total of 7,064 juvenile lobsters were tagged using Hallprint T-anchor tags. Each was identified with a unique 6-digit number. All tags were inserted ventrally, using a Dennison tag-fast® III tag applicator, into the anterior oblique muscle between the first and second abdominal sterna. Data recorded upon initial tagging and subsequent recapture included location, sex, CL, depth, and sexual maturity based on setal development. Recaptures were also reported by the commercial and recreational sectors in all areas.

### Data analyses

Juvenile size frequency was analysed by comparing the initial size class of all releases with initial size classes of all recaptures. This was achieved using histograms with 5 mm CL (carapace length) bin classes for both sexes.

Percentages of lobsters tagged and recaptured below and above the maximum peak size class in each site were statistically compared using a chi-square test. Distance moved by recaptured lobsters was analysed using ArcView GIS (Version 8.3).

# Results

## Size Frequency – Pigeon Holes

Of the 7,064 lobsters tagged, a total of 1,030 were recaptured (14.58 %). The majority of male lobsters initially tagged and released at Pigeon Holes ranged from 45-95 mm CL (Figure 47). The initial size of male recaptures primarily ranged from 45-65 mm CL with 66% of all male recaptures initially tagged in this range. Recapture rates of male lobsters initially tagged above 70 mm CL were low at Pigeon Holes. This was confirmed by chi-square analysis that identified significantly fewer males above the 65-69 mm CL size class in recaptures (Table 10). Initial size of female lobsters tagged and released at pigeon Holes ranged between 45-89 mm CL (Figure 48). Recaptures were highest in female lobsters that were initially tagged between 45 – 74 mm CL. In total, 79% of all female recaptures were initially tagged in this range.

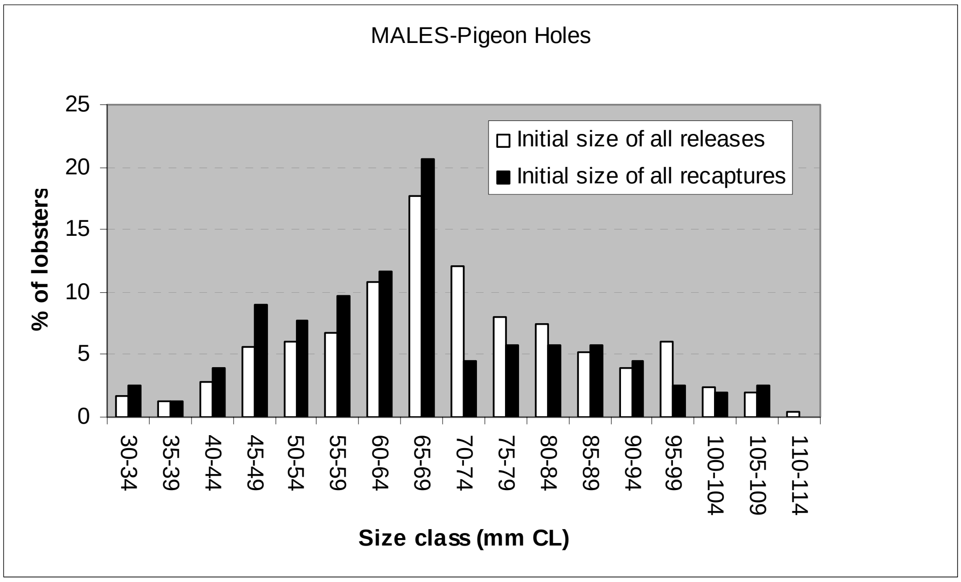

**Figure 47. Initial size of all releases and recaptures for male lobsters tagged at Pigeon Holes.**

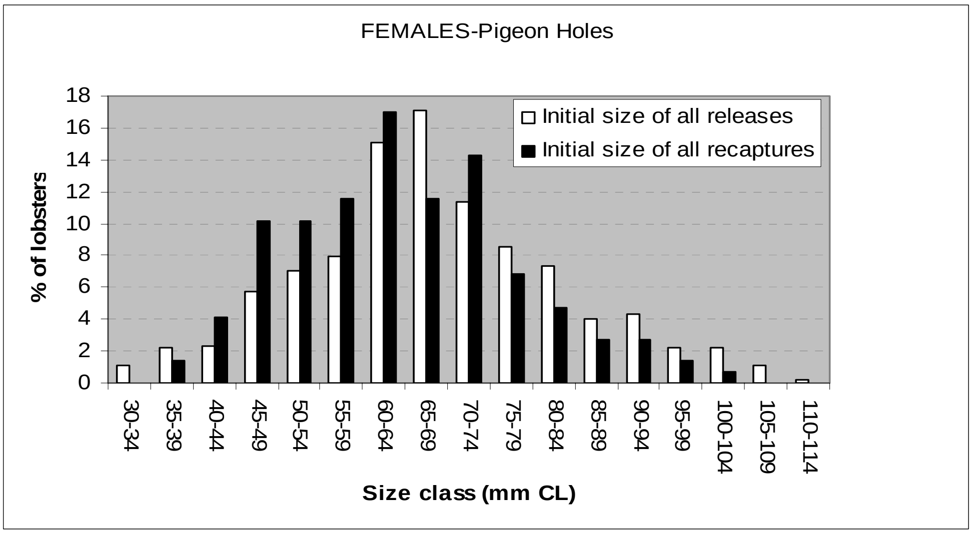

**Figure 48. Initial size of all releases and recaptures for female lobsters tagged at Pigeon Holes.**

## Size Frequency – Livingstons

The majority of male lobsters initially tagged and released at Livingstons ranged from 45-89 mm CL (Figure 49). The initial size of male recaptures primarily ranged from 45-79 mm CL with 65% of all male recaptures initially tagged in this range. Of particular note was the 50-54 mm CL size class where 16% of all lobsters were recaptured. Initial size of female lobsters tagged and released also ranged between 45-89 mm CL (Figure 50). Recaptures were highest in female lobsters that were initially tagged between 45 – 74 mm CL. In total, 83% of all female recaptures were initially tagged in this range.

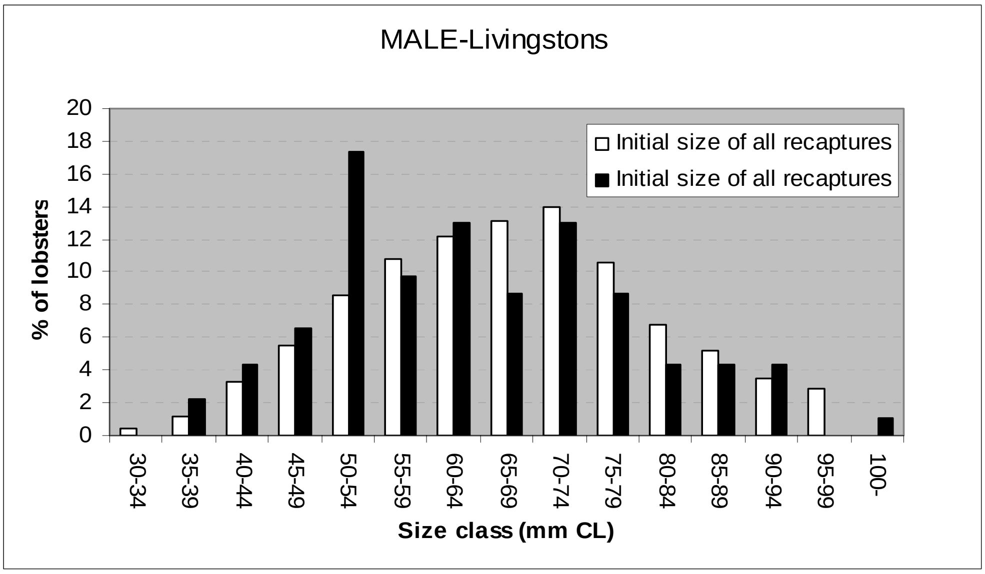

Figure 49. Initial sizes of all releases and recaptures for male lobsters tagged at Livingstons.

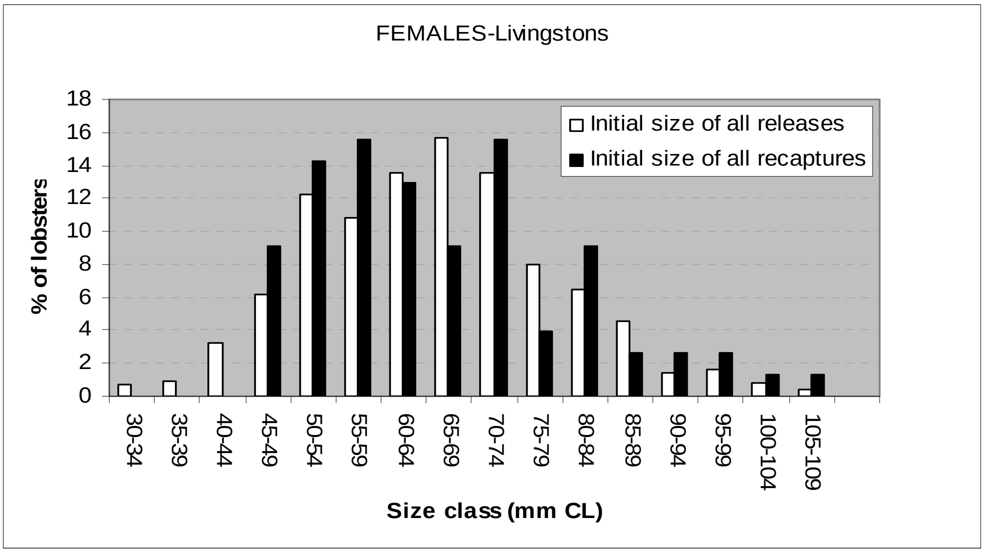

Figure 50. I nitial sizes of all releases and recaptures for female lobsters tagged at Livingstons.

## Size frequency – Glenvar

The majority of male lobsters initially tagged and released at Glenvar ranged from 35-99 mm CL (Figure 51). The initial size of male recaptures primarily ranged from 50-94 mm CL with 79% of all male recaptures initially tagged in this range. Initial size of female lobsters tagged and released also ranged between 40-84 mm CL (Figure 52). Recaptures were highest in female lobsters that were initially tagged between 55 – 99 mm CL. In total, 85% of all female recaptures were initially tagged in this range. At Glenvar, recaptured female lobsters appeared to be over represented in the larger size classes. This was confirmed by chi-square analysis that identified significantly more females above the 70-74 mm CL size class in recaptures (Table 10).

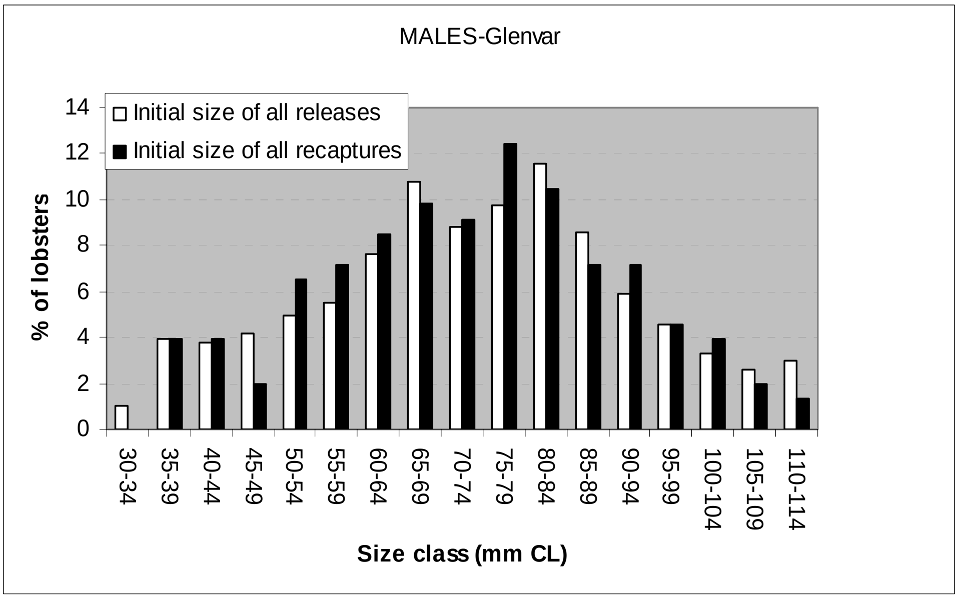

**Figure 51. Initial sizes of all releases and recaptures for male lobsters tagged at Glenvar.**

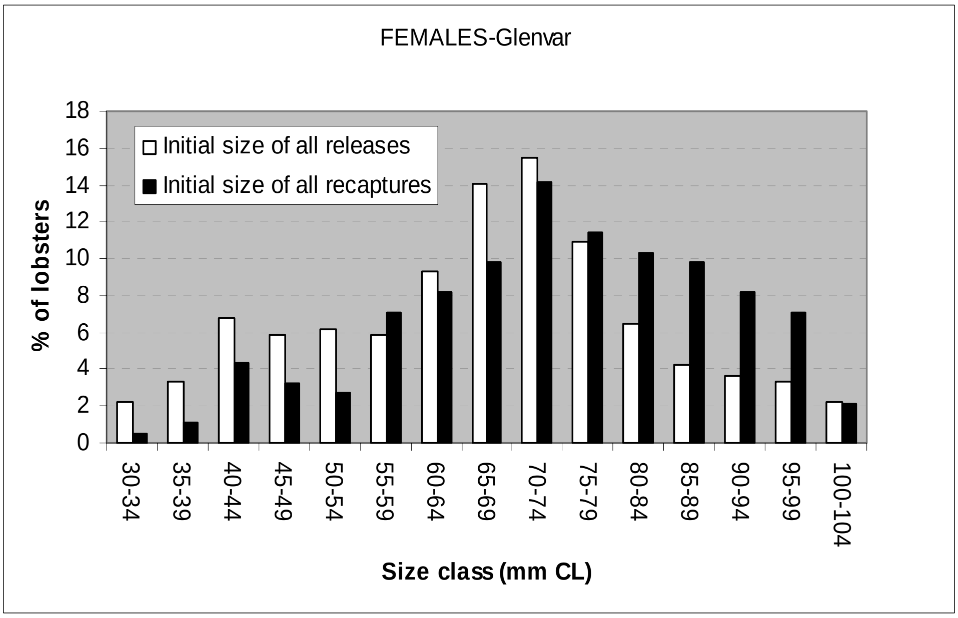

**Figure 52. Initial sizes of all releases and recaptures for female lobsters tagged at Glenvar.**

**Table 10. Percentage of lobsters tagged and recaptured below and above the maximum peak size class in each site.**

| Site | Sex | Max. peak | % tagged < max. peak | % recap < max peak | % tagged >= max. peak | % recap >= max. peak | P Value |
|---|---|---|---|---|---|---|---|
| **Pigeon Holes** | Male | 65-69 | 37% | 49% | 63% | 51% | P < 0.05 |
| **Pigeon Holes** | Female | 65-69 | 40% | 46% | 60% | 54% | P > 0.05 |
| **Livingstons** | Male | 70-74 | 43% | 67% | 57% | 33% | P > 0.05 |
| **Livingstons** | Female | 65-69 | 50% | 54% | 50% | 46% | P > 0.05 |
| **Glenvar** | Male | 80-84 | 45% | 45% | 55% | 55% | P > 0.05 |
| **Glenvar** | Female | 70-74 | 55% | 36% | 45% | 63% | P < 0.05 |

P values calculated from chi-square test comparing percentages of recaptures (observed) versus initially tagged (expected).

## Movement

Overall, data on movement rates of juveniles were limited. Observed movement rates as estimated from lobsters recaptured within the sample sites, were low with only 2.2% of lobsters moving distances > 100 metres from their original capture location. This can be expected, given that sampling was only undertaken within sites and not in adjacent areas.

Some insight into size related movement, while limited, was achieved through recapture data from the commercial and recreational sectors in areas outside of the sample sites (Table 11). Across all sites, all observed movement only occurred in lobsters initially tagged in size classes above 60 mm CL. No lobsters below this size range were recaptured outside of the release sites. Distance moved ranged from 0.1 to 7 km but most lobsters were located >3 km from their release location. No apparent difference in movement was observed between sexes. In South Australia, all lobsters were found to have moved in an offshore direction (Figure 53).

**Table 11. Details of lobsters recaptured from commercial and recreational sectors.**

| Release Location | Sex | Initial length (mm CL) | Final length (mm CL) | Distance moved (km) |
|---|---|---|---|---|
| **Port Campbell** | F | 97 | 100 | 0.2 |
| | F | 111 | - | - |
| | M | 88 | 103 | 5.8 |
| | M | 108 | 107 | 0.1 |
| | M | 75 | 112 | 4.4 |
| **Livingstons** | F | 81.1 | 101.7 | 6.3 |
| | F | 61.2 | 81.2 | 3.3 |
| | F | 86 | 86 | 5.8 |
| | F | 79 | 110 | 6.9 |
| | M | 63 | 124 | - |
| | F | 91 | 103.5 | 6.6 |
| | F | 73.5 | 89 | 2.85 |
| **Pigeon Holes** | M | - | - | 7 |
| | M | - | - | 7 |

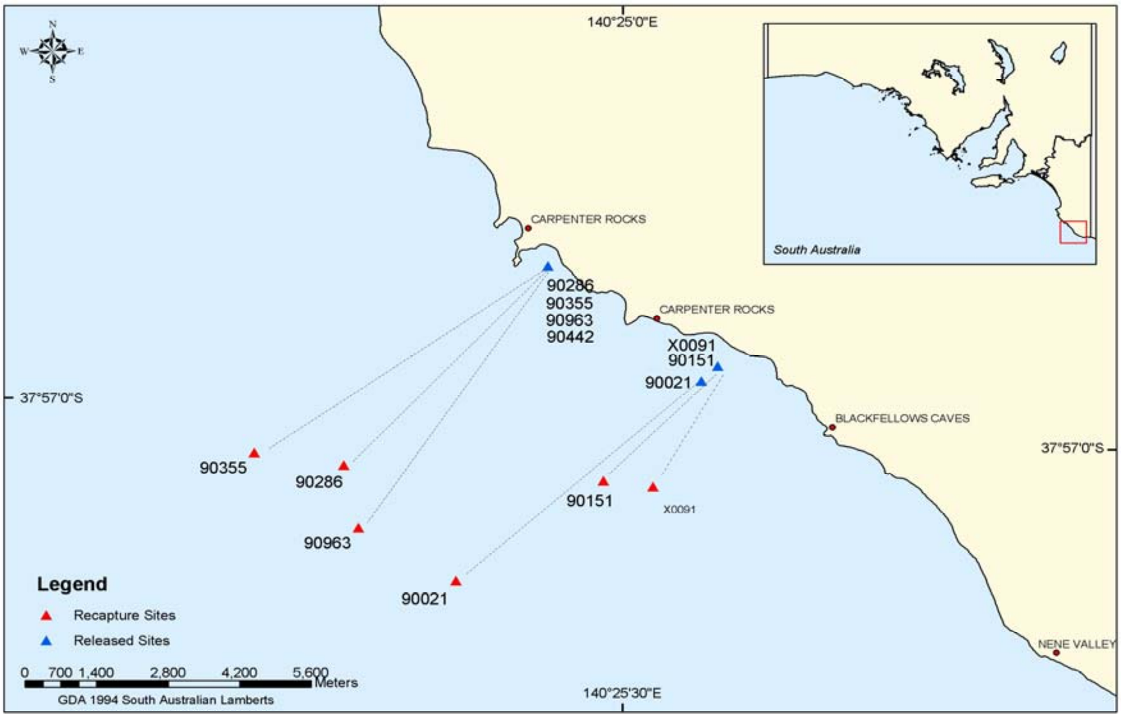

**Figure 53. Map of study area in South Australia showing direction of movements by lobsters away from the initial release site at Livingstons.**

# Discussion

Size frequency analyses of male and female lobsters, particularly at Pigeon Holes and Livingstons sites suggested that the smaller size classes of initially tagged individuals, especially within the 45-70 mm CL range, were more represented in the recaptures. Whether this is a result of higher survival by these individuals, or higher rates of tag loss, tag induced mortality or emigration by larger size classes is unknown. Of particular note was the lack of recapture data from the 30-39 mm CL size range. Tag induced mortality may be a plausible explanation. Tag-related mortalities in other crustacean species have been linked to the quality of handling, condition of animal at tagging, and individual circumstances of each experiment. Tagging of lobsters by inserting dart or T-bar anchor tags causes a wound that may lead to necrosis in the inter-segmental membrane and surrounding muscle tissue (Winstanley, 1976). Working with *Jasus lalandii*, Dubula et al., (2005) recorded a 33% mortality for 75-90 mm CL lobsters tagged with T-bar tags. A T-bar tag size affect has also been identified in the Scyllarid lobster *Thenus indicus* where low recapture rates of the smaller size classes was accredited to smaller individuals being less tolerant to the physical trauma of tagging (Courtney et al., 2001).

While recaptures of lobsters outside the study areas were low, the results suggested that lobsters above 60 mm CL moved more than other size classes. Size specific movement patterns in *Jasus edwardsii* are well documented. In South Australia, 65% of all lobsters observed to move > 1 km (from 14, 280 tag returns) were in the 75-100 mm CL size class (Linnane et al., 2005). Specifically, immature females moved significantly more than any other size class of males of females. In New Zealand, Street (1969, 1971) first reported this movement pattern in tagged lobsters released in Otago, Foveaux Strait, and Fiordland between 1957 and 1970. In all instances, lobsters which moved long distances were sexually immature females ranging from 90 to 105 mm CL. Similarly, Annala & Bycroft (1993) reported that the largest proportion of lobsters observed to migrate in Fiordland were immature females that moved in a northerly direction.

Significantly higher rates of movement in immature lobsters have also been recorded in Victoria (Treble 1996) and Tasmania (Pearn 1994). Booth (1997) suggested that higher levels of migration by immature females might be a response to approaching maturity so that these lobsters would be in regions more favourable to larval survival. In several Panulirids there are recorded long distance migrations to enable females to release their offspring in favourable current systems e.g. *Panulirus ornatus* (Moore & MacFarlane, 1984). Specifically, the mechanism allows for the dispersal of larvae away from inshore reef-dwelling planktivores. Other potential benefits of movement, particularly to offshore sites, include access to new feeding grounds (Kelly et al. 1999) and avoidance of seasonal changes in inshore salinity (Watson et al. 1999). Similar size-related characteristics of movement by immature individuals have also been reported for other spiny lobster species namely *Panulirus cygnus* (Phillips 1983), *P. argus* (Davis & Dodrill 1989), *Palinurus gilchristi* (Groeneveld & Branch 2002) and *P. delagoae* (Groeneveld 2002).

In the current study, no sampling apart from recreational and commercial fishing was undertaken outside of the study areas. As a result, some lobsters may have undertaken significant movements, but were undetected. Tag returns from the recreational and commercial fishery sector during the course of upcoming fishing seasons should provide a more comprehensive dataset.

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# Chapter 9 - Linking puerulus to catch

## Introduction

The southern rock lobster (*Jasus edwardsii*) fishery is one of the most valuable across Tasmania, Victoria and South Australia with approximately ~4000 tonnes landed annually at a commercial value of ~AUS$150 million. All three states are managed by quota management controls that are influenced by outputs from a number of stock assessment models (Punt and Kennedy 1997; McGarvey *et al*. 1997). Model outputs include estimates of recruitment to the fisheries that are largely driven by commercial catch and effort data. Future predictions of recruitment under a range of quota scenarios can be calculated but tend to have a high degree of uncertainty. The ability to predict future recruitment to the fishery based on puerulus settlement indices is therefore a desirable tool in the management of the resource as it provides improved accuracy to such model outputs.

Puerulus monitoring has broadly 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-range settlement trends and early life history morphology. The focus changed, however, with the success in both New Zealand with *Jasus edwardsii* (Breen and Booth 1989) and Western Australia with *Panulirus cygnus* (Phillips 1986; Caputi *et al*. 1995) of utilising puerulus settlement indices in predicting future recruitment to the fishable biomass. Specifically, in Western Australia total commercial catch was successfully predicted from settlement indices using a 3 – 4 year time lag.

While the settlement–recruitment relationship has been proven in some fisheries, in others, a range of factors have been shown to distort the correlation. Puerulus settlement levels typically vary both spatially and temporally. On a large scale, spatial variability is related to the closeness of settlement sites to the source of puerulus (Booth and Phillips 1994). On a finer scale, variability can be influenced by local hydrology and oceanographic conditions. Temporal variations in lobster settlement are largely related to ocean climate. In particular, lobster settlement in Western Australia appears correlated to changes in the El Nino Southern Oscillation (ENSO) index (Clarke and Li 2004). The settlement-recruitment relationship is also affected by variability surrounding density-dependent growth rates (Booth et al 2001) and the absence of a relationship between catches on collectors and settlement on surrounding habitat (Butler and Herrnkind 1991; Butler *et al*. 1995).

The aims of this component of the study were to identify:

- Seasonal patterns in monthly settlement indices across South Australia, Tasmania and Victoria
- Annual patterns in settlement indices between sites
- Correlations between puerulus settlement and model estimated recruitment across sites.
- In Tasmania, this work updates the previous correlations identified by Gardner *et al*. (2001).

## Methods

### South Australia

Data used for analysis were taken from five puerulus monitoring sites located in the southern zone rock lobster fishery (SZRLF) of South Australia. The sites are located at Blackfellows Caves, Livingstons Beach, Beachport, Cape Jaffa and Kingston (Figure 55) and have been in place since 1991. As in Victoria and Tasmania, the collectors are similar in design to those described by Booth and Tarring (1986) consisting of angled wooden slats that mimic natural crevice habitat (Figure 54). Collectors on all sites are serviced monthly with details of the sampling protocol provided in Linnane *et al* (2005). Indices of settlement are calculated as mean number of puerulus per collector.

Estimates of recruitment to the fishery are derived from the qR stock assessment model for the fishery (McGarvey and Mathews 2001). In summary, the qR model fits to the yearly catch by weight (Cw, in kg) and numbers (Cn, in numbers of lobsters landed). Effort (E, as potlifts) is taken from logbook data and a Baranov-Schaefer catch relationship (Cn=qEN) is assumed, where an estimated catchability parameter, q, relates model-predicted catch in number bi-linearly to both effort and population number of legal-size lobsters (N). The model likelihood is written as a modified normal and fitted numerically. Recruitment in each year is estimated as a free parameter.

**Figure 54. A crevice collector as used in South Australia, Victoria and Tasmania for puerulus settlement.**

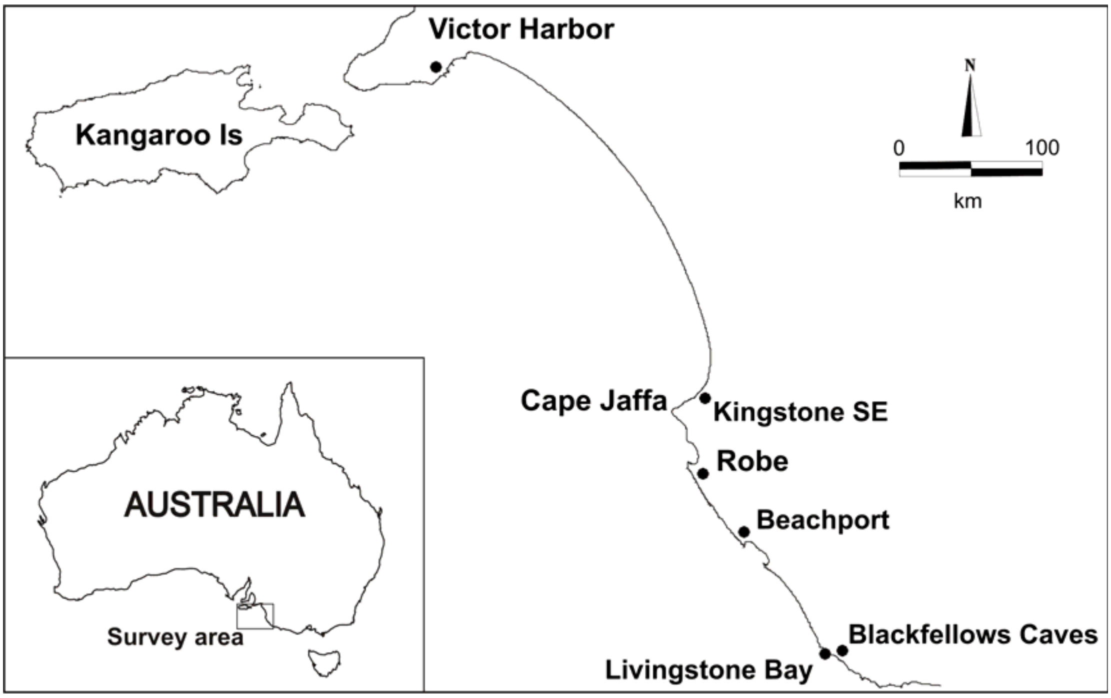

**Figure 55. Location of puerulus monitoring sites in the Southern Zone Rock lobster Fishery (SZRLF) of South Australia.**

## Tasmania

Details of the design and layout of the Tasmanian puerulus monitoring sites are provided in previous publications (Kennedy *et al.* 1994; Gardner *et al.* 1998). Collectors are deployed on sand at depths of 3 to 9 m in areas adjacent to reef at five sites in Tasmania (Figure 56). Collectors on all sites are serviced monthly with details of the sampling protocol provided in Gardner et al (2001). Indices of settlement are calculated as mean number of puerulus per collector.

Settlement estimates for the Tasmanian resource were obtained for each of the eight stock assessment areas for each year from 1970 to 2004 (Figure 57). These yearly settlement values were obtained through the length-based stock assessment model described by Punt and Kennedy (1997) with modifications as described by Gardner *et al.* (2005). The population dynamics model is size and sex structured and is fitted to commercial catch and effort data plus research length-frequency data.

Yearly settlement values are defined in the model as the number of animals that reach the smallest length considered (10 mm). This implies that lags between settlement and recruitment are already accounted for in these estimates. Current time lags for each of the eight stock assessment areas (Figure 57) are as follows: Area 1=5 years, Area 2=4 years, Area 3=4 years, Area 4=3 years, Area 5=3 years, Area 6=4 years, Area 7=4 years and Area 8=6 years. It is important to note that the growth transition data in the model are derived from tag-recapture of lobsters from 80 mm CL upwards (Punt *et al.* 1997). Thus the estimated time for growth from settlement to recruitment involves extrapolation with an associated risk of error. The process of back-calculating settlement values also implies that model generated estimates of settlement for recent years are not fitted to data because there is insufficient lag between catch rate data and settlement. Therefore, more recent years of model-estimated settlement have been excluded from analyses presented here.

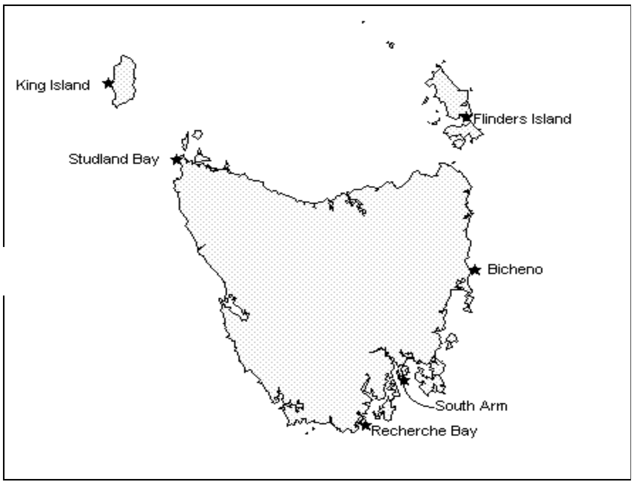

**Figure 56. Location of Tasmanian puerulus collector sites. Sites were established in 1991 at King Island, Bicheno, South Arm, and Recherche Bay. The Flinders Island site was established in December 1995. Sampling at Studland Bay has been discontinued.**

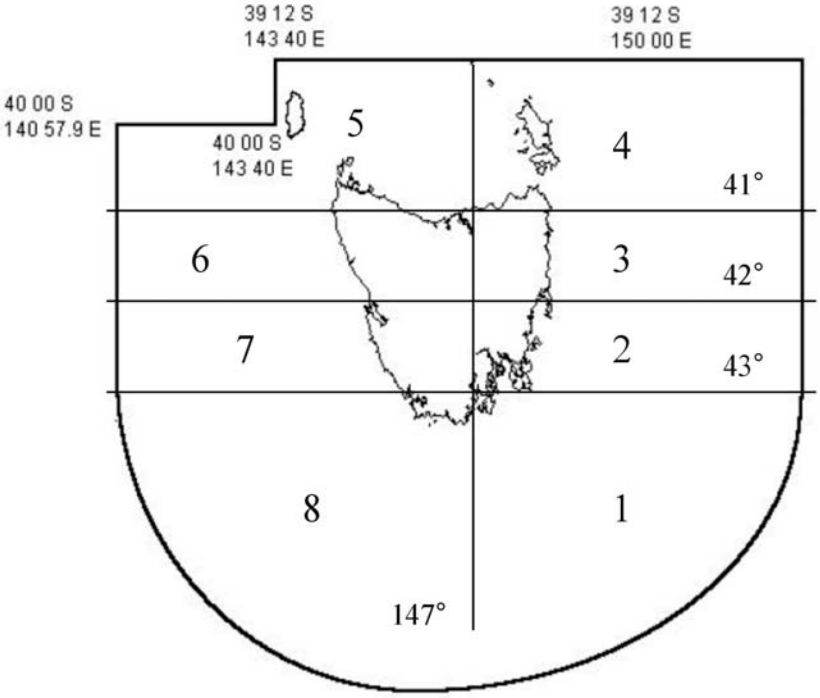

**Figure 57. The boundaries of the eight Tasmanian Stock Assessment Areas and the area of State waters for the rock lobster fishery provided by the offshore constitutional settlement (OCS).**

## Victoria

Data used for analysis were taken from two puerulus monitoring sites located at Port Campbell and Apollo Bay in Victoria (Figure 58). The estimates of model recruitment are obtained through the length-based stock assessment model described by Punt and Kennedy (1997). In Victoria, parameters related to growth, natural mortality, and selectivity are determined from auxiliary analyses (see Hobday & Punt (2001) for details). The remaining parameters of the model such as the mean recruitment over the assessment period and the logarithms of the annual deviations in recruitment about the mean recruitment, are determined by fitting it to data on catch-rates, the length-frequency of the commercial catch, and estimates of the annual catches in numbers (Punt and Kennedy 1997; Hobday and Punt 2001). There is evidence that recent recruitment has been lower than historical recruitment (particularly for the eastern management zone), so future recruitment is determined by random sampling from the recruitments for the last 10 years of the assessment period, which mimics (to some extent) the possible implications of a stock-recruitment relationship.

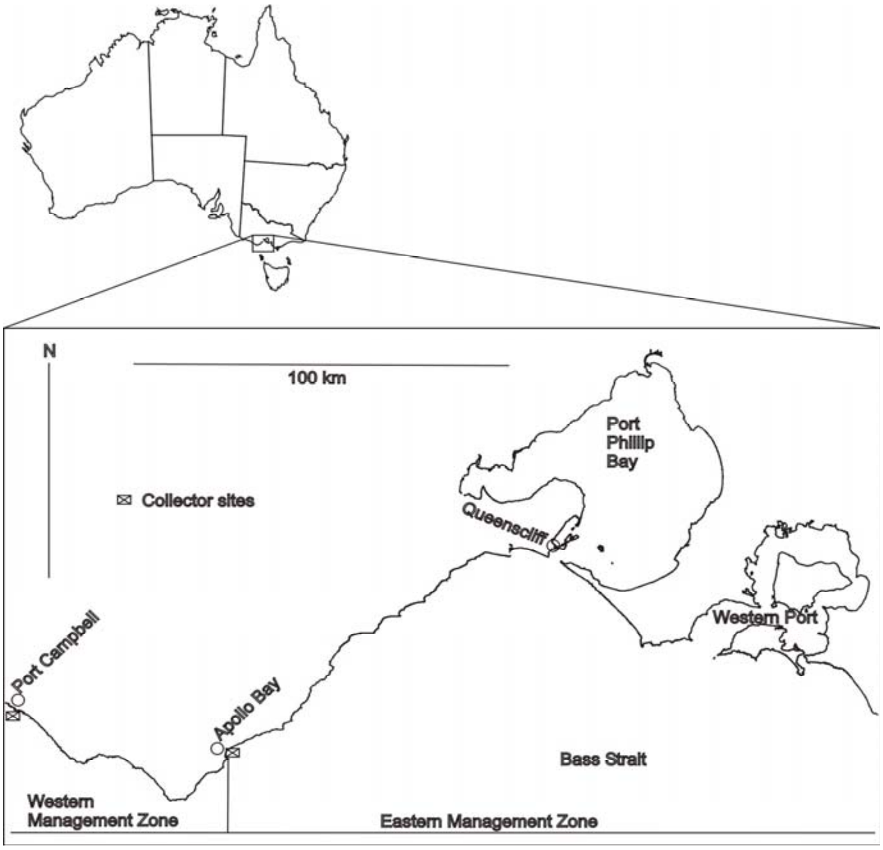

**Figure 58. Location of puerulus monitoring sites in Victoria at Port Campbell and Apollo Bay.**

### Data Analyses

Seasonal patterns of settlement were identified through monthly counts of puerulus in all collector sites. A puerulus settlement index (PSI) was then calculated as the mean number of puerulus per collector. Within season comparisons were calculated as the monthly deviations within each site from the mean annual settlement index. Relative settlement values, as calculated by dividing each monthly settlement index by the largest index for that area, were used to compare seasonal trends across regions.

Annual trends were compared using the PSI from months of peak settlements were observed. The relationship between puerulus settlement indices and model recruitment outputs were tested using Pearson product-moment *r*-values.

## Results

### Seasonal patterns of settlement

A strong seasonal pattern in settlement was observed across all three states (Figure 59). Two deviations from the mean annual settlement were observed annually. The most prominent occurred in South Australia and Tasmania during the winter months, and was highest in August. A deviation from mean settlement was also observed in Victoria in August, but on a much lower scale.

The second deviation from the mean was evident in May/June in South Australia and Victoria. Both were less than that of Tasmania where the second deviation was greatest in April. Overall, Victoria had the lowest levels of deviation on a monthly basis from mean annual settlement whereas deviations in settlement were greatest in Tasmania.

The relative trend in puerulus settlement was very similar across regions (Figure 60). In particular, Victoria and Tasmania have very similar patterns at the beginning of the season, with all three regions having peaks in relative settlement values in August before decreasing as the season progresses.

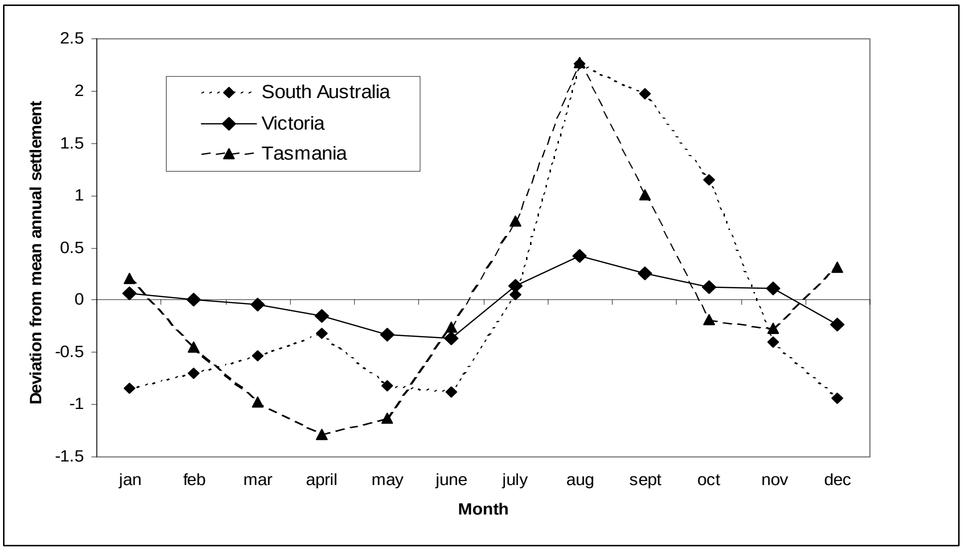

**Figure 59.** Seasonal patterns in settlement across South Australia, Tasmania and Victoria. Data points are calculated as monthly deviations from mean annual settlement in each region.

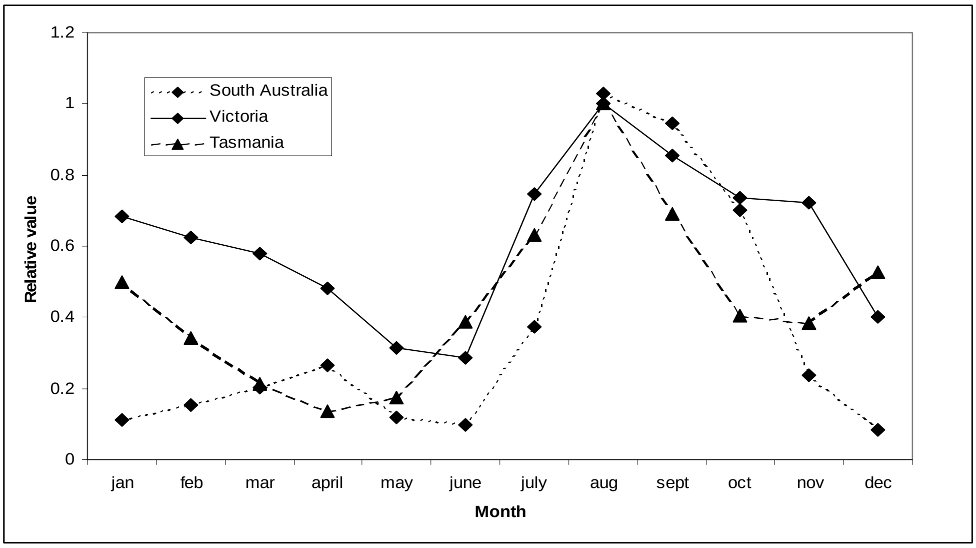

**Figure 60.** Comparison of seasonal settlement trends between South Australia, Victoria and Tasmania.

## Annual settlement patterns

Annual patterns in PSI in all three States from 1994 to 2003 are presented in Figure 61. As with seasonal data, there appears to be some correlation in observed patterns across sites. In particular, South Australia and Victoria had similar settlement trends (*r*-value 0.55). Comparable peaks in PSI were observed in both South Australia and the western zone of Victoria in both 1998 and 2002. Low or decreasing PSI was consistent across both sites in 1997, 2000 and 2003. Tasmanian (King Island site) peaks in settlement in 1995 and 2002 also correspond to similar peaks in South Australia, as do settlement troughs in 1997 and 2000.

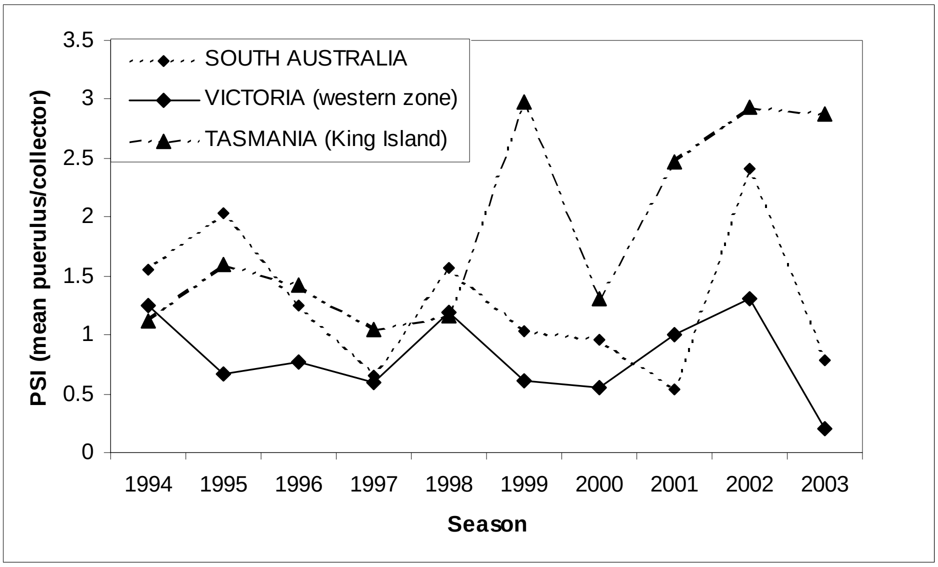

**Figure 61. Annual patterns in settlement across South Australia, Tasmania and Victoria from 1994 to 2003. Annual data points are calculated from mean settlements during peak settlement months in each state.**

## Correlations between puerulus settlement and recruitment

### South Australia

Interannual trends in puerulus settlement index (PSI) and model estimated recruitment (to the minimum legal size of 98.5 mm CL) were similar over the period 1995 to 2003 (Figure 62). Using a four year time lag between settlement and recruitment, correlation analysis resulted in $r^2$ values of 0.58 over 9 overlapping time series. The comparative trends are strongest over the period 1995 and 1999 ($r^2$=0.80). Of note was the observed decrease in puerulus settlement in 1997, which was not matched with a decrease in model recruitment in 2001. Clearly, the number of overlapping data points are limited in South Australia, as the puerulus sampling programme has only been in place since 1991. Nonetheless, the overall patterns indicate that puerulus indices can be used to predict future recruitment to the fishery.

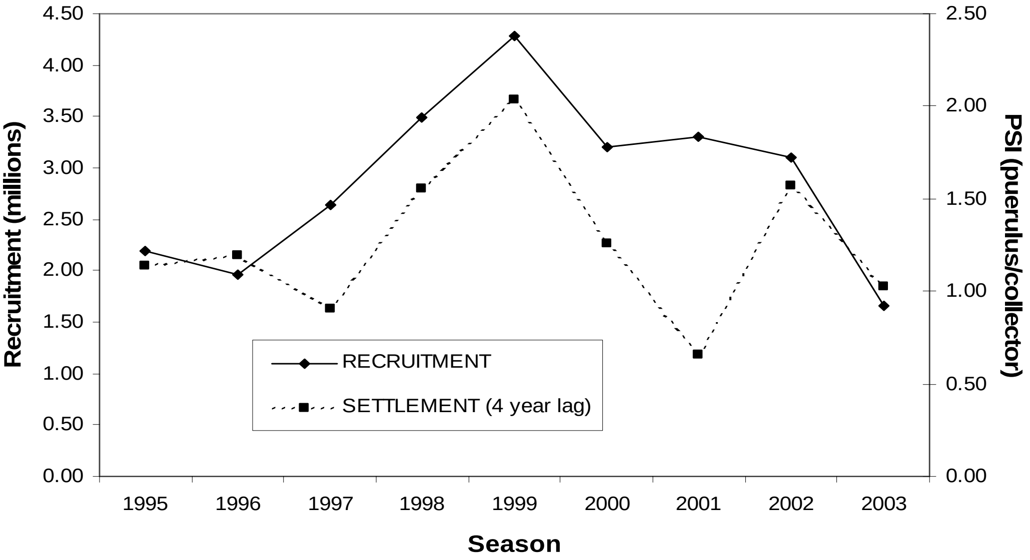

Figure 62. **Correlations between model estimated recruitment and puerulus settlement index (PSI) lagged by 4 years in South Australia ($r^2 = 0.58$).**

### Victoria

Interannual trends in puerulus settlement index (PSI) and model estimated recruitment (at 80 mm CL) were similar over the period 1997 to 2002 in the western rock lobster fishing zones of Victoria (Figure 63). Using a 2 year time lag between settlement and recruitment correlation analysis resulted in $r^2$ values of 0.46 over 7 overlapping data points. Of significance was the increase in settlement observed in 2001, which was reflected by an increase in recruitment in 2003.

A good correlation was also observed in the eastern zone over 9 over lapping seasons ($r^2$=0.69) (Figure 64). Of particular note were the peaks in recruitment observed in 1996 and 2000 that correlated to peaks in PSI two years previous. The observations support the hypothesis that puerulus indices can be used to predict recruitment in Victoria.

### Tasmania

Interannual trends in PSI and model estimated recruitment (at 80 mm CL) were observed in four Tasmanian sites (**Error! Reference source not found.**). Using a 1 year time lag between settlement and recruitment, a correlation ($r^2$=0.63) was observed across 11 overlapping time series at Bicheno and 8 overlapping time series at Flinders Island ($r^2$=0.55). Of particular note was the observation that peaks in recruitment at both sites in 1996 (Bicheno) and 1998 (Flinders) were tracked by peaks in puerulus settlement lagged by 1 year. At King Island, a correlation ($r^2$=0.92) was only observed across 5 time series between 1998 and 2002 using a two year lag. In Recherché Bay, a three year time lag revealed a correlation between recruitment and PSI in the overlapping period from 1996 to 2002 ($r^2$=0.39). As stated previously, lags between settlement and recruitment are already accounted for in model estimated recruitment in Tasmania (see materials and methods for specific lags). Taking the additional lags identified in the current analysis into account, this suggests that the time between settlement and recruitment is over a period of 4-5 years in northeastern sites (e.g. Flinders Island) and eastern Tasmania (e.g. Bicheno), but increases to 8 years at southeastern Tasmania (e.g. Recherché Bay). The findings, particularly at Bicheno and Flinders Islands confirm the observations of Gardner et al., (2001) concerning the emerging relationship between puerulus settlement and recruitment in Tasmania.

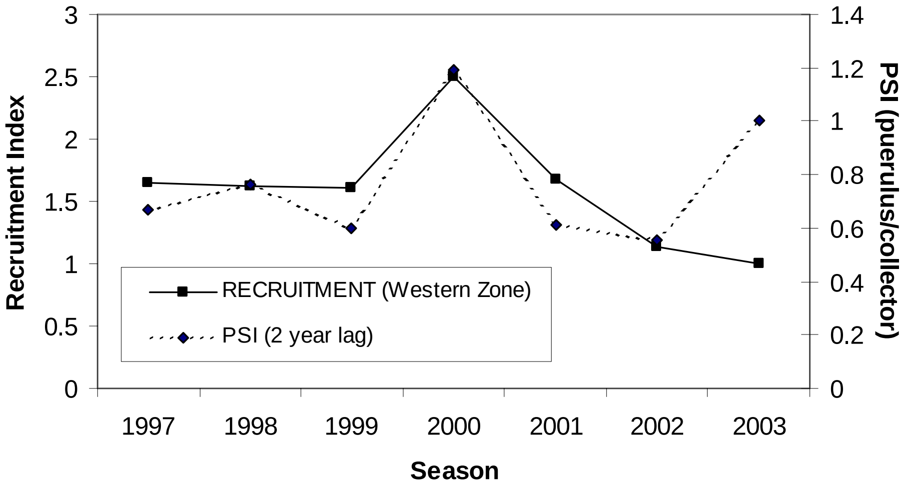

**Figure 63.** **Correlations between model estimated recruitment (at 80 mm CL) and puerulus settlement index (PSI) lagged by 2 years in the western rock lobster fishing zone of Victoria ($r^2 = 0.46$).**

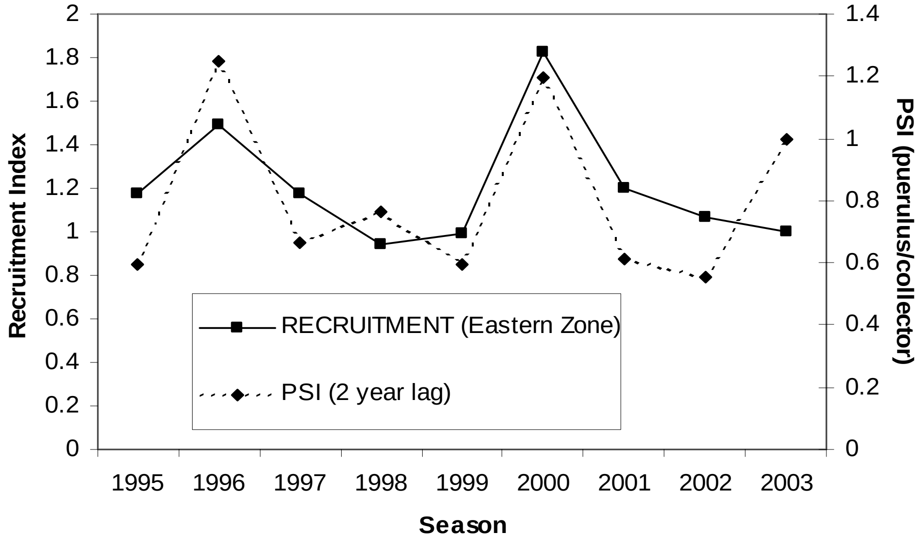

**Figure 64.** **Correlations between model estimated recruitment (at 80 mm CL) and puerulus settlement index (PSI) lagged by 2 years in the eastern rock lobster fishing zone of Victoria ($r^2 = 0.69$).**

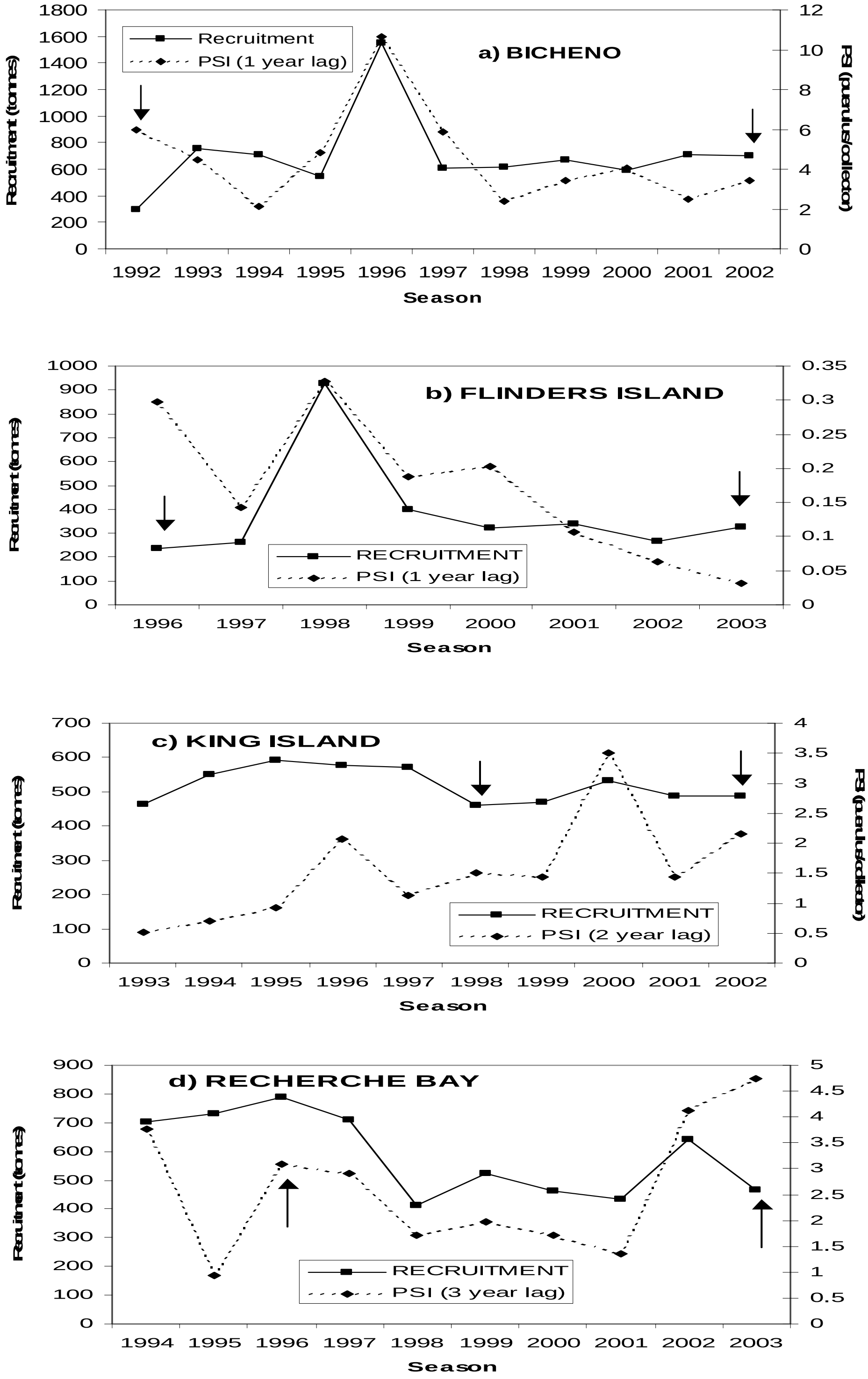

**Figure 65.** Correlations between model estimated recruitment (at 80 mm CL) and puerulus settlement index (PSI) Tasmania using various time lags at a) Bicheno (r2 = 0.63) b) Flinders Island (r2 = 0.55), c) King Island (r2 = 0.92) and by 3 years at d) Recherche Bay (r2 = 0.39). Arrows indicate the beginning and end of the time series where correlations were found.

# Discussion

Within season patterns of settlement were strongly correlated in each of the sampling sites. Settlement was highest during the winter months with peak settlement observed in August in each state. A second, less prominent settlement peak can sometimes occur in December/January in Tasmania and Victoria and in March/April in South Australia. Seasonal patterns in settlement have also been identified for *J. edwardsii* in New Zealand (Booth 1994) as well as the western rock lobster *Panulirus cygnus* (Morgan *et al.* 1982). Temporal correlations with settlement across all sites indicate that a common broad-scale physical transport mechanism controls within season settlement. The strong correlation with high settlement during winter months indicates that wind speed and direction is a possible mechanism for inshore transport of offshore phyllosoma. Harris *et al.* (1988) correlated westerly winds with yearly total harvest in the Tasmanian fishery while McGarvey and Mathews (2001) suggested that yearly recruitment might be related to mid-winter western wind strength five to seven years earlier in South Australia. The less significant mid summer settlement peak observed in this study has also been recognised in New Zealand populations where shelf width and closeness to retentive gyre features are also known to influence within season settlement (Booth 1994).

Physical processes may not be the only explanation for temporal correlations of recruitment across all sites. The seasonal availability of a large pool of pueruli competent to settle only in winter may also play a role. Specifically, results from Chapter 3 of this report indicate that the timing of settlement within a year is important in determining the timing of recruitment to the fishery. With substantial changes in growth rates depending on exposure to summer or winter water temperatures, puerulus settling at different times within a year would grow at different rates. Within a 12 month period starting in July, when the largest settlement peak in *J. edwardsii* occurs, puerulus that settle between July and October would be of similar size at the end of June of the following year. After October, the decreased time available for growth is not compensated for by the summer water temperatures and puerulus reach a smaller final size by the end of June. As July to October is the largest of the settlement peaks in all sites, these animals would be expected to contribute to a similar recruitment peak in the fishery.

Annual trends in settlement indices were also correlated across sampling sites. Factors known to influence settlement include initial levels of larval production, length of larval life, abundance of predators, climatic and oceanographic conditions (Booth 1994; Booth *et al.* 2000). Local factors influencing settlement are exposure to currents, position of collectors in relation to open sea and amount of natural habitat competing with collectors. Despite this, the high correlation observed across the three sites in this study and in particular, the correlation of high settlement years, strongly suggests that factors affecting settlement are common and widespread. In western Australia, the effects of El Nino events on the strength of the Leeuwin current appear to correlate with annual settlement and subsequent recruitment in *P. cygnus* (Clarke and Li, 2004*)*. Specifically, shelf edge flows in western Australia weaken during El Nino years thus reducing the transport of phyllosoma to inshore coastal areas. The effects of major currents on settlement patterns in the current sample sites remain largely unknown. Future research in South Australia however, aims to focus on the effects of the South Australian and Zeehan currents on settlement and recruitment patterns in a number of important commercial species (S. McClatchie, SARDI Aquatic Sciences, pers. comm.).

The ability to predict future recruitment to the fishery based on annual settlement indices is a vital tool, particularly in relation to fisheries management. Current time series remain limited, as most quantitative puerulus sampling programs did not begin until the early to mid 1990s. As a result, overlapping time series data between puerulus settlement index (PSI) and model estimated recruitment are restricted in some sites. Nonetheless, the correlations observed across all sampling sites indicate that prediction of recruitment is viable. Using a two-year time lag, PSI was strongly correlated to recruitment at 80 mm CL in both fishing zones of Victoria. Correlations were also evident in Tasmania in three sampling locations albeit in fewer overlapping seasons. In northeastern Tasmania recruitment is relatively fast with an average period of 4 years between settlement and recruitment to the fishery. In regions further south, the time between settlement and recruitment increased to 5 years at eastern Tasmania and 8 years at southeastern Tasmania. The increase in time between settlement and recruitment to the fishery is expected due to the decline in average water temperatures (and therefore slower growth rates) with increasing latitude although the magnitude of the lag is greater than originally ‘guesstimated’.

A four-year time lag from settlement to recruitment into the fishable biomass was identified in South Australia across nine overlapping seasons. The link between puerulus indices and recruitment has also been reported in New Zealand for *J. edwardsii* (Breen and Booth 1989; Booth et al. 2000) and in Western Australia for *P. cygnus* (Phillips,1986; Caputi *et al*. 1995). In the latter, commercial catch rates are routinely predicted from settlement indices using a four year lag.

The use of model estimated recruitment as an indicator of stock size has clear advantages. Previous comparisons between puerulus catches and changes in the stock were based on catch rate data (Gardner *et al*. 2001), however, since that time considerable stock rebuilding has occurred in many of the sampling sites (Gardner *et al.* 2005; Linnane *et al,* 2005;). As a result, catch rates in all fisheries are now strongly influenced by the dynamics of the fleet and the population dynamics of fully recruited cohorts, rather than year-to-year variation in recruitment. Model estimates of settlement 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 sites in all States are of value to predicting future recruitment to the fishery. Longer time series trends will improve the understanding of the puerulus-recruitment relationship as more data becomes available.

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# Results/Discussion – whole study

This project commenced research into one of the most difficult life history phases of the southern rock lobster *Jasus edwardsii*. Although the species supports significant commercial and recreational fisheries in South Australia, Victoria, Tasmania and New Zealand, there is limited information available on the post-settlement phase. That is, the period between settlement as puerulus and recruitment to the commercial fishing gear (at approximately 80 mm CL). A major contributing factor to this knowledge gap is the difficulty in sampling in the complex temperate reef habitat typical of southern Australia.

Given the complex and extended larval life cycle of spiny lobsters and the potential dispersal capacity of the larvae in oceanic systems, it is considered unlikely that a link between egg production and puerulus settlement will be achieved. In contrast, once recruited to the temperate reef ecosystem, the link between puerulus settlement and future catches would appear more feasible.

While linking puerulus settlement to future fishery catches has been achieved for the Western Australian fishery for *Panulirus cygnus*, the western rock lobster, the ecosystem is less complex than in southern Australia. Southern Australia temperate reefs are bathed by a number of differing current systems that bring differing nutrient concentrations. The oceanographic aspects of the *P. cygnus* larval cycle is relatively well understood and time from puerulus settlement to recruitment into the fishery relatively short at 4 years. In contrast, the larval history of *J. edwardsii* in southern Australia is not well understood, and time between settlement and recruitment is considered to be variable. At the regional scale, the building blocks for the reefs consist of a variety of different rock types that offer different habitat complexity. Associated with the physical conditions is a diverse and complex array of sessile flora and fauna. Additional regional scale influences that make the southern Australian story more complex than that in Western Australia also include the enormous range in exposure of reefs on which rock lobsters occur.

In attempting to extend our knowledge of the post-settlement phase of the lobster life cycle two major challengers faced this project. The first was to determine how an appropriate number of post-puerulus and juveniles could be routinely sampled in a complex environment. The second was to determine methods that would provide robust and accurate measures of growth and survival, the two main parameters required to link puerulus to future catches.

Edmunds (1995) estimated that juvenile *J. ed*wardsii shift from a solitary to a more gregarious lifestyle at approximately 35 – 40 mm CL in southern Tasmania. The first opportunity for divers to sample lobsters in meaningful numbers occurs when the lobster adopt this gregarious lifestyle. They are also at a size where they are easier to sight in the algal forests of most temperate reefs. Prior to this change in lifestyle, the solitary post-puerulus is extremely difficult to find and therefore virtually impossible to undertake any quantitative experimentation.

To determine growth rates and survival of the solitary phase of post-puerulus, we explored the use of artificial reefs (Chapter 5). A pilot project confirmed the potential for aerated concrete (Hebel) to be a suitable substrate and the size of holes for maximising puerulus retention. Puerulus that were sourced from routine puerulus settlement monitoring programs were tagged using micro-wire tags and added to the artificial reefs. Artificial reefs located in the Derwent Estuary on sand were able to retain puerulus for up 355 days during which the animals grew to a size of approximately 40 mm CL. During the first year after settlement puerulus could grow to between 35 mm CL and 50 mm CL depending on the average water temperature for the 12 month period (Chapter 3). Water temperature accounted for the majority of the variation found in growth rates and the monthly average water temperatures could predict the expected size of post-puerulus in their first year. Puerulus that settled during the first three months of the main winter settlement period (July – September) would all be of similar size by June of the following year. Thus the main settlement peak (see Chapter 7) would contribute to a single mode by the middle of the following year. During this study, puerulus showed significant differences in growth rates by season although there was no difference due to sex.

The extremely low number of puerulus available to be added to the artificial reefs compromised survival estimates during this study. Nonetheless, we were able to demonstrate the potential for using multiple mark and recapture models to obtain estimates of survival and identify experimental designs that would enhance the potential to improve precision of these estimates. In this study we were able to obtain an annual survival estimate (Chapter 6). The survival estimate was substantially higher than reported for other species of spiny lobsters. This may be associated with the use of the artificial reefs, the placement of the artificial reefs on sand, or it may reflect that survival is high in this location. Further experimentation is required to separate these confounding effects. Of interest was the low resighting rate of puerulus added to an artificial reef placed on natural reef. The East Coast region of Tasmania where the artificial reef was located has consistently produced the largest settlement indices of all the Tasmanian puerulus settlement monitoring sites indicating that the region is suitable for puerulus. The lack of resighting in this region may be associated with either higher mortalities associated with the adjacent suite of reef predators or a preference for puerulus and post-puerulus to move off the artificial structure into the neighbouring reef. Further research to separate these issues is required.

It is unknown what cues puerulus use to seek appropriate benthic habitat as they swim from oceanic waters, and what habitat (physical shape and structure and type of sessile community) conveys greatest survival potential. Outcomes of this study demonstrate that artificial reefs hold promise for exploring the behaviour and ecological requirements of puerulus and post- puerulus.

More traditional mini-T-bar tags were used to tag juvenile lobsters once they reached the gregarious stage of approximately 40 – 50 mm CL. Combining both the outputs from the stochastic model and the moult increment analysis provided insights into the process of juvenile growth that would not be achieved by either analysis alone. Growth estimates demonstrated that prior to maturity there was little difference in the moult increment between male and female lobsters although the frequency of moulting declined more rapidly in females resulting in lower annual growth rates (Chapter 4). Growth rates varied by site with fastest growth in Eastern Tasmania. The high growth rates were further supported by the large size at onset of maturity.

Survival estimates demonstrated both increases and declines in survival with time for the sites where sufficient recaptures were available. Irrespective of the trend in survival with time, none of the estimates of the larger lobsters approximated the survival estimate of legal-size lobsters. The size frequency distributions showed a rapid decline in the size structure of lobsters after approximately 60 – 70 mm CL although the steepness of the decline varied with each site. In general the steeper the decline in larger lobsters the lower the survival estimates of the larger lobsters. Comparison of the site that was manipulated to enhance lobster numbers with the adjacent control site indicated that initial survival of the lobsters at the manipulated site was higher than the control after which survival declined in the manipulated site and increased in the control site. If emigration is accounting for the lower than expected survival estimates as suggested above, it appears that the response to enhancement of the reef was an increased emigration rate. The consistency in the survival estimate of lower size class of juveniles between sites in South Australia, Eastern Tasmania and the Derwent Estuary suggests that the substantial differences in habitat and environmental conditions between these sites has limited impact on survivorship of this size class. The lack of larger sized lobsters in all the sites surveyed is surprising. Two of these sites (Glenvar Bay and Pigeon Holes) are located on the eastern side of the Derwent Estuary directly opposite a lobster reserve known for its large population of above legal sized lobsters. Similarly the East Coast site at Point Leuseur is adjacent to the Maria Island Marine Reserve, also known for its large population of legal size lobsters. Recreational diving and trapping for lobsters is also common in regions adjacent to the survey sites in Eastern Tasmania and South Australia. These results indicate that the size structure and behaviour of inshore lobster is more complex than initially considered and this study has provided insights that will lead to further experimentation to unravel the complex relationship between juvenile lobsters and their environment.

It is not surprising that this, the first study to attempt to fill the gap in knowledge about survival and growth in post-settlement juvenile lobsters, has raised more questions than it has answered. Southern temperate reefs are arguably some of the most complex and dynamic in Australia and provide researchers with considerable logistical and technical difficulties. The success of the study is measured in both its provision of the first estimates of parameters important for linking puerulus to future catches and its demonstration of methodologies that can be used for future studies.

Future experimental designs that account for the difficulties encountered in this study will build on the knowledge gained and continue the task of understanding the complex behaviour of puerulus and juvenile lobsters on inshore temperate reefs.

Density manipulations only increased densities by approximately 15% and this resulted in no significant change in growth of juveniles although the enhanced reef in the Derwent Estuary demonstrated a decline in survival with size, presumably due to enhanced emigration from the reef. While it could be concluded that this reef was at peak carrying capacity and thus unable to support increased juveniles, extrapolation of these results is unwise. The puerulus survival estimate for this region is higher than reported elsewhere for spiny lobsters and while this could be associated with the use of artificial reefs, the juvenile survival estimates for the smaller size group was also substantially higher than for the other reefs surveyed. The higher survival would result in carrying capacity being saturated quicker than usual. As none of the reefs surveyed in this project supported populations of larger lobsters, these reefs could be considered as 'feeder' reefs for other regions. While a bottleneck in carrying capacity may be attributed to these reefs for supporting populations of larger lobsters, this type of bottleneck would not impact on the fishery if it simply resulted in greater emigration rates from the reef. While inconclusive, 'feeder' reefs have not been reported previously for southern rock lobster and this concept has implications for management of this important life history phase of southern rock lobster and the importance of inshore reefs in sustaining fishery production.

Annual puerulus settlement patterns were surprising consistent for South Australia, Victoria and Eastern Tasmania considering that these regions are affected by different oceanic conditions and are different distances from the continental shelf. Of particular interest is the large increase in relative settlement from June to August in each State (Chapter 7). While the cue for this rapid increase in settlement is unknown, the consistent pattern across all States strongly suggests that the factors affecting recruitment are common and widespread. Future studies should aim to identify the processes involved.

All the southern rock lobster fisheries in Southern Australia are under individual transferable quota (ITQ) management systems. The South Australian and Tasmanian fisheries have been under ITQs for the longest periods and have seen substantial rebuilding of legal sized biomass. Catch rates in the fishery therefore reflect a combination of recruitment of lobsters and increased growth by previously recruited lobsters. To overcome these confounding effects we used the model estimates of recruitment that account for the impacts of a rebuilding biomass. Overlap periods between model recruitment estimates and puerulus settlement indices varied from 7 to 11 years depending on the time each State implemented their puerulus monitoring programs. Fortunately, within each region where puerulus settlement sites have been established, there has been considerable contrast between annual settlement indices. This contrast has enabled peaks in puerulus settlement to be matched to peaks in model recruitment. In northern regions of the fishery (Victoria, Northeastern Tasmania and South Australia), recruitment is relatively fast with an average period of 4 years between settlement and recruitment to the fishery. In regions further south, the time between settlement and recruitment increased to 5 years at eastern Tasmania and 8 years at southeastern Tasmania. The increase in time between settlement and recruitment to the fishery is expected due to the decline in average water temperatures (and therefore slower growth rates) with increasing latitude although the magnitude of the lag is greater than originally 'guestimated'. The greater the time lag between settlement and recruitment to the fishery, the greater the potential for annual settlement peaks to overlap. This was reflected in the weaker correlation for the southern site. Within each region there is at least one period where the match between settlement and recruitment fails, the cause for this is uncertain and will need a longer time series of data before processes can be linked to these patterns. For the majority of data points there is a strong positive correlation indicating the potential for puerulus settlement indices to be used for future management of the resource.

# Benefits

The major beneficiary of the research will be the users of the southern rock lobster resources. This includes government managers, commercial and recreational fishers.

Other beneficiaries will be scientists who undertake research on rock lobster resources to provide advice to Industry and Management.

The project has provided the first estimates of growth rates from puerulus to pre-recruit lobsters that can be incorporated into the assessment of this species. Although puerulus growth was restricted to southern regions of the fishery, results demonstrate a strong relationship with water temperature that could result in site specific growth rates being obtained from knowledge of water temperatures (see further development). Importantly, we were able to demonstrate that different puerulus settlement peaks have different impacts on future recruitment to the fishery. Different settlement peaks can now be more accurately incorporated into assessment models. This is expected to improve the precision of future predictions that are currently used to set catch targets (quotas) in each State.

The project has also provided the first estimates of survival of puerulus and juveniles between settlement and recruitment to the fishery. There remains uncertainty about bottlenecks in the juvenile phase due to the discovery that certain reefs may act as nursery or feeder reefs. This finding has implications for management of inshore reefs and the positioning of marine protected areas.

For Tasmania, we are able to provide a first estimate of survival in the first year that can be used by lobster aquaculture if the reseeding option is used for puerulus harvesting and ongrowing.

The combination of research methods using micro-wire and mini-T-bar tags, artificial and natural reefs and the latest development in mark recapture analysis has provided a powerful tool for obtaining growth and survival estimates for this difficult period of life-history. Despite complications with poor puerulus settlement that resulted in low and infrequent additions of puerulus to the artificial reefs and fewer and irregular harvests, results indicate that the methods used are robust to such circumstances.

# Further Development

Due to the alteration of the design of the artificial reefs for deployment in SA and the subsequent destruction by storms (see section 5), no estimates of puerulus growth were available from the northern range of the species. Additional research to confirm if the same relationship holds between growth rate and water temperature for southern Tasmania should be undertaken. If the relationship is maintained then temperature loggers could be used to determine more precise estimates of recruitment to the fishery from puerulus settlement indices and thus future catch targets.

Further development would be the incorporation of recruitment (puerulus to pre-recruit) models within the main lobster stock assessment models in each state.

Further development would also be the linking of juvenile cohorts with the undersized catch in pots. The undersized catch (eg. 70-90mmCL) can be used as an indicator of future recruitment. However, recent research on selectivity of pots indicates that the resultant catch in pots is a composite of a range of biological and physical processes. Manipulating reefs to increase density, as undertaken in the project, and combining underwater surveys with potting surveys would provide calibration factors for pots. This would enable the use of puerulus indices for longer-range predictions and then these would be refined as juveniles began to enter pots.

The status of nursery or feeder reefs requires further exploration. Such reefs could potentially be of significant importance to offshore and deeper water regions. Special management requirements similar to mangroves in northern Australia or shark nursery zones could be considered.

# Planned Outcomes

In bold are the outcomes we identified in B6 of the original application

1. **Incorporation of post-settlement growth and survival information into future stock assessments in each state. Both managers and industry will benefit from this outcome as it will provide greater certainty and lower associated risk in TACC forward projections.**

This project has provided the first estimates of growth and survival of juvenile southern rock lobster from regions adjacent to fishing regions in SA, Vic and Tas. Estimates cover major differences in the range of temperatures that the fishery operates in. Although the first year estimate of post-puerulus growth was only obtained from Tasmania, this data can provide an approximate estimate for both SA and Vic. These outputs will be available for each State to incorporate into their stock assessment models.

We were also able to show that puerulus that settle over the peak settlement period of July to October contribute to a single cohort by the middle of the following year. This enables future assessments to attribute settlement indices to future cohorts.

2. **Managers and industry will be provided with a "lead in" time on which to rationalise future harvests once future harvests can be predicted from puerulus/juvenile indices.**

The combined growth rates of puerulus and juveniles from the different regions of the resource enables each state to be able to predict with greater certainty the impact of changes in puerulus settlement indices on future catches. The growth rates of juveniles also enable greater certainty in the prediction of future catches from surveys that target any of the undersized stages (eg. juveniles from underwater surveys or from pots). Interpretation of juveniles from pot catches requires careful consideration as mentioned under Further Developments.

3. **A fundamental contribution to the understanding of the mortality and survival of early life history stages in lobster.**

The project has produced the first estimates of post-puerulus and juvenile survival and how survival varies with increased abundance. In addition to the estimates the project demonstrated methodologies that can be used to obtain these estimates.

4. **Improvements in the yield of the lobster fishery arising out of better management.**

The finding that some reefs support adult populations while others don't demonstrates the complexity of inshore ref systems. The extent to which inshore reefs support offshore and deeper water populations is unknown. The substantially lower estimate of survival for larger lobsters compared to the estimates from the commercial fishery suggest that there are either significant mortality events or emigration rates. Similarly, it is not possible to conclude that the lower survival estimates for larger lobsters on the enhanced reefs was due to greater emigration or increased mortality due to a bottleneck survival. However, the positive correlation between settlement indices and catches suggest that no substantial bottleneck occurs, especially as high settlement indices result in increased catches. Frusher et al (2003) postulated that there had been declines pre-recruits in the southern rock lobster fishery associated with declining legal sized biomass. This project demonstrates that any improvement in puerulus numbers settling on our coasts should result in a greater legal sized biomass and thus improved yields in the fishery. The current adoption of ITQs in southern rock lobster fisheries has resulted in a rebuilding of legal sized biomass in most regions. Once a temporal time series of puerulus settlement has been obtained from each State it will be possible to determine if this biomass is resulting in greater numbers of recruits.

5. **Increased confidence in the biological neutrality of puerulus harvest and reseeding associated with the new lobster aquaculture industry.**

Prior to this project there was considerable uncertainty regarding the fate of puerulus during their first year. An aquaculture reseeding option had been developed between the wild fishery, aquaculture and the Government to maintain biological neutrality while allowing harvest of puerulus. The concept was based on “reseeding” a portion of the lobsters back onto reefs after they had been harvested and held in culture. The portion was to be at least equivalent to juveniles that would have survived during the first year in the wild. This report provides more robust estimates of the number that should be returned and also the approximate size of the juveniles that should be returned.

# Appendix 1: Intellectual Property

No commercially valuable intellectual property resulted from this research.

Results are provided with no protection or confidentiality.

# Appendix 2: Staff

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# Appendix 3: Size-transition matrices

| **SA Female** | **20** | **25** | **30** | **35** | **40** | **45** | **50** | **55** | **60** | **65** | **70** | **75** | **80** | **85** | **90** | **95** | **100** | **105** | **110+** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **20** | 0.0006 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **25** | 0.0442 | 0.0009 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **30** | 0.1910 | 0.0553 | 0.0012 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **35** | 0.2580 | 0.2180 | 0.0694 | 0.0018 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **40** | 0.2100 | 0.2690 | 0.2460 | 0.0872 | 0.0026 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **45** | 0.1360 | 0.2040 | 0.2770 | 0.2770 | 0.1100 | 0.0038 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **50** | 0.0783 | 0.1240 | 0.1940 | 0.2820 | 0.3090 | 0.1390 | 0.0057 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **55** | 0.0419 | 0.0670 | 0.1100 | 0.1810 | 0.2820 | 0.3410 | 0.1750 | 0.0087 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **60** | 0.0213 | 0.0338 | 0.0556 | 0.0946 | 0.1640 | 0.2740 | 0.3710 | 0.2200 | 0.0134 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **65** | 0.0103 | 0.0161 | 0.0262 | 0.0444 | 0.0784 | 0.1430 | 0.2600 | 0.3960 | 0.2770 | 0.0208 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **70** | 0.0048 | 0.0074 | 0.0117 | 0.0194 | 0.0337 | 0.0620 | 0.1200 | 0.2360 | 0.4110 | 0.3450 | 0.0329 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **75** | 0.0021 | 0.0032 | 0.0049 | 0.0079 | 0.0134 | 0.0241 | 0.0461 | 0.0945 | 0.2040 | 0.4120 | 0.4260 | 0.0527 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **80** | 0.0009 | 0.0013 | 0.0020 | 0.0031 | 0.0050 | 0.0086 | 0.0159 | 0.0316 | 0.0690 | 0.1640 | 0.3910 | 0.5160 | 0.0855 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **85** | 0.0003 | 0.0005 | 0.0007 | 0.0011 | 0.0017 | 0.0028 | 0.0050 | 0.0094 | 0.0195 | 0.0453 | 0.1200 | 0.3430 | 0.6070 | 0.1400 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **90** | 0.0001 | 0.0002 | 0.0002 | 0.0003 | 0.0005 | 0.0008 | 0.0014 | 0.0025 | 0.0048 | 0.0102 | 0.0254 | 0.0752 | 0.2670 | 0.6770 | 0.2310 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **95** | 0.0000 | 0.0000 | 0.0001 | 0.0001 | 0.0001 | 0.0002 | 0.0003 | 0.0005 | 0.0010 | 0.0019 | 0.0043 | 0.0112 | 0.0373 | 0.1700 | 0.6930 | 0.3770 | 0.0000 | 0.0000 | 0.0000 |
| **100** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0001 | 0.0001 | 0.0001 | 0.0003 | 0.0005 | 0.0012 | 0.0033 | 0.0122 | 0.0745 | 0.6090 | 0.5960 | 0.0000 | 0.0000 |
| **105** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0001 | 0.0001 | 0.0004 | 0.0017 | 0.0141 | 0.4040 | 0.8770 | 0.0000 |
| **110+** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0001 | 0.1230 | 1.0000 |

| SA Male | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 | 110 | 120 | 130 | 140 | 150+ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **20** | 0.0241 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **30** | 0.1770 | 0.0288 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **40** | 0.3270 | 0.2090 | 0.0350 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **50** | 0.2990 | 0.3630 | 0.2500 | 0.0433 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **60** | 0.1410 | 0.2850 | 0.3970 | 0.3010 | 0.0548 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **70** | 0.0295 | 0.1000 | 0.2540 | 0.4250 | 0.3650 | 0.0711 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **80** | 0.0021 | 0.0127 | 0.0600 | 0.2040 | 0.4350 | 0.4450 | 0.0951 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **90** | 0.0000 | 0.0004 | 0.0037 | 0.0272 | 0.1380 | 0.4130 | 0.5390 | 0.1320 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **100** | 0.0000 | 0.0000 | 0.0000 | 0.0006 | 0.0079 | 0.0707 | 0.3430 | 0.6390 | 0.1920 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **110** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0010 | 0.0224 | 0.2260 | 0.7110 | 0.2930 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **120** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0027 | 0.0974 | 0.6920 | 0.4610 | 0.0000 | 0.0000 | 0.0000 |
| **130** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0156 | 0.5390 | 0.6990 | 0.0000 | 0.0000 |
| **140** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.3010 | 0.9520 | 0.0000 |
| **150+** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0482 | 1.0000 |

| Tas Female | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 | 100 | 105 | 110 | 115 | 120 | 125+ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **20** | 0.0131 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **25** | 0.0956 | 0.0146 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **30** | 0.1980 | 0.1060 | 0.0163 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **35** | 0.2490 | 0.2160 | 0.1190 | 0.0184 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **40** | 0.2210 | 0.2620 | 0.2360 | 0.1330 | 0.0210 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **45** | 0.1410 | 0.2180 | 0.2740 | 0.2590 | 0.1500 | 0.0240 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **50** | 0.0618 | 0.1250 | 0.2100 | 0.2840 | 0.2840 | 0.1710 | 0.0277 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **55** | 0.0177 | 0.0468 | 0.1060 | 0.1970 | 0.2900 | 0.3100 | 0.1950 | 0.0323 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **60** | 0.0030 | 0.0107 | 0.0328 | 0.0849 | 0.1790 | 0.2920 | 0.3380 | 0.2240 | 0.0381 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **65** | 0.0003 | 0.0013 | 0.0057 | 0.0208 | 0.0634 | 0.1550 | 0.2860 | 0.3660 | 0.2590 | 0.0455 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **70** | 0.0000 | 0.0001 | 0.0005 | 0.0026 | 0.0115 | 0.0429 | 0.1260 | 0.2710 | 0.3920 | 0.3020 | 0.0552 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **75** | 0.0000 | 0.0000 | 0.0000 | 0.0001 | 0.0009 | 0.0054 | 0.0255 | 0.0932 | 0.2450 | 0.4130 | 0.3530 | 0.0680 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **80** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0002 | 0.0020 | 0.0126 | 0.0611 | 0.2050 | 0.4230 | 0.4140 | 0.0856 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **85** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0005 | 0.0048 | 0.0335 | 0.1550 | 0.4140 | 0.4850 | 0.1100 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **90** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0001 | 0.0013 | 0.0142 | 0.1000 | 0.3780 | 0.5640 | 0.1460 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **95** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0002 | 0.0040 | 0.0507 | 0.3080 | 0.6420 | 0.1990 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **100** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0006 | 0.0174 | 0.2100 | 0.6960 | 0.2800 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **105** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0030 | 0.1050 | 0.6900 | 0.4050 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **110** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0001 | 0.0295 | 0.5940 | 0.5800 | 0.0000 | 0.0000 | 0.0000 |
| **115** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0018 | 0.4200 | 0.7820 | 0.0000 | 0.0000 |
| **120** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.2180 | 0.9850 | 0.0000 |
| **125+** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0150 | 1.0000 |

| **Tas Male** | **20** | **30** | **40** | **50** | **60** | **70** | **80** | **90** | **100** | **110** | **120** | **130** | **140** | **150** | **160** | **170+** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **20** | 0.0106 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **30** | 0.1730 | 0.0132 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **40** | 0.4670 | 0.2100 | 0.0166 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **50** | 0.3120 | 0.5080 | 0.2570 | 0.0211 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **60** | 0.0359 | 0.2530 | 0.5370 | 0.3150 | 0.0275 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **70** | 0.0003 | 0.0155 | 0.1850 | 0.5460 | 0.3870 | 0.0367 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **80** | 0.0000 | 0.0000 | 0.0049 | 0.1170 | 0.5250 | 0.4740 | 0.0501 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **90** | 0.0000 | 0.0000 | 0.0000 | 0.0010 | 0.0605 | 0.4660 | 0.5720 | 0.0704 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **100** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0001 | 0.0233 | 0.3720 | 0.6720 | 0.1020 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **110** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0056 | 0.2570 | 0.7550 | 0.1530 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **120** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0006 | 0.1430 | 0.7920 | 0.2340 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **130** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0551 | 0.7560 | 0.3590 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| **140** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0095 | 0.6410 | 0.5200 | 0.0000 | 0.0000 | 0.0000 |
| **150** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0002 | 0.4800 | 0.6900 | 0.0000 | 0.0000 |
| **160** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.3100 | 0.8600 | 0.0000 |
| **170+** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.1400 | 1.0000 |