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FRDC Project 1998/302 – Rock Lobster Enhancement and Aquaculture Subprogram:

Towards establishing techniques for large scale harvesting of pueruli and obtaining a better understanding of mortality rates

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Fisheries research in Western Australia

The Fisheries Research Division of the Department of Fisheries is based at the Western Australian Marine Research Laboratories, P.O. Box 20, North Beach (Perth), Western Australia, 6920. The Marine Research Laboratories serve as the centre for fisheries research in the State of Western Australia.

Research programs conducted by the Fisheries Research Division and laboratories investigate basic fish biology, stock identity and levels, population dynamics, environmental factors, and other factors related to commercial fisheries, recreational fisheries and aquaculture. The Fisheries Research Division also maintains the State data base of catch and effort fisheries statistics.

The primary function of the Fisheries Research Division is to provide scientific advice to government in the formulation of management policies for developing and sustaining Western Australian fisheries.

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FRDC Project 1998/302 – Rock Lobster Enhancement and Aquaculture Subprogram:

Towards establishing techniques for large scale harvesting of Pueruli and obtaining a better understanding of mortality rates

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Objectives

To determine appropriate puerulus to legal size survival rates and potential harvesting ratios, that if implemented in the western rock lobster fishery, might result in 'biological neutrality' being achieved.

To establish techniques for large scale harvesting of pueruli for rock lobsters.

Non-technical summary

An estimate was made of the rates of survival of western rock lobster, (*Panulirus cygnus*) pueruli, from when they swim inshore and settle on the inshore reefs at the end of the larval stage, to when they reach legal size and recruit to the fishery between 3 and 5 years of age. The results indicated that pueruli and post pueruli are subject to very high mortality. Estimates of mortality occurring during the first year after settlement in the region between 29°S-30°S, which is near to the centre of the commercial fishery were as high as 97-98%, and at least 80-84%. Between 0.9 and 6.4% were estimated to survive between settlement and recruitment to the fishery at about 4.5 years of age.

Because of this high natural mortality, the impact of puerulus removals on subsequent catches was estimated to be minimal except in the case of removal of very large quantities of pueruli in low settlement years. It was shown that it would be possible to counter even these small losses by effort reductions (i.e. reducing fishing pressure), if this was thought necessary. For example, if it was decided to harvest 20 million pueruli from the 29°S–30°S latitude area in an average year, when puerulus settlement size was about 600 million, approximately 1% of pots could be removed to maintain the size of the breeding stock. This converts to about 23,000 pot lifts or about 100 pots (approximately 22 t of catch) for the season.

This information provides industry and managers with the basis to evaluate proposals that involve puerulus collection and recommend possible levels of reduction in fishing effort to compensate.

Investigations into developing methods to catch large numbers of pueruli found that the pueruli will be easiest to catch near the shore (depths <5 m), and in locations with fringing reefs. A modified western rock lobster collector, called the sandwich collector, was the most successful for catching the western rock lobsters pueruli, and proved to be robust and easily handled. For highest catches the collectors need to be set out in an array, and daily servicing (i.e. removing pueruli from the collectors) for seven days around the time of new moon, yielded catches 170% higher than those obtained from a single monthly servicing. The site in which the collectors are to be located, needs to be selected after trialling the area with a series of collectors set out over a range of positions along the coast.

Other western rock lobster pueruli harvesting methods were trialled. Neither fixed nets (plankton nets which are set in a fixed position to face prevailing water currents), pump nets (benthic nets which produce a jet of current to expose shallow sand-burrowing fauna), or mid-water trawling, proved to be effective methods for catching pueruli in quantity.

Studies in Tasmania, by the Tasmanian Aquaculture and Fisheries Institute, showed that southern rock lobster pueruli could be caught in several collectors including bag and sandwich collectors. These achieved good catch rates when deployed in an alternative fashion (on the seafloor for southern rock lobsters versus at the surface for western rock lobsters). Some pueruli of *Jasus edwardsii* emigrate from collectors after settlement and yield was shown to be greatest when the collectors were serviced at intervals of one week or less during peak settlement periods. Pueruli were lost during the hauling of collectors from the seafloor to the boat, with some escaping whilst hauling to the surface and others being washed from collectors as they were hauled clear of the surface. The use of a scoop net to lift collectors into the boat helps avoid this problem.

The Final Report to FRDC includes a suggested Protocol for operation of the collectors to catch pueruli.

Commercial collection of southern rock lobster pueruli for aquaculture has already commenced in Tasmania, and the Rock Lobster Industry Advisory Committee in Western Australia stated in March 2001, that the project paves the way for a small scale commercial pilot operation collecting puerulus from the northern zone of the fishery for grow out (the on-growing of pueruli to a marketable sized lobster).

The first part of this study examined the impact of possible puerulus exploitation on the catches of the commercial fishery for the western rock lobster, *Panulirus cygnus*, in Western Australia, and determined management measures which might be required to maintain 'biological neutrality'. A primary aim of management to maintain sustainability of the Western Rock Lobster Fishery, is to maintain the reproductive capacity of the breeding stock at a level sufficient to replenish itself. In this context, biological neutrality is the level of catch that would need to be forgone to compensate the reproductive capacity of the breeding stock if pueruli were removed for aquaculture.
Catch-puerulus relationships over the whole fishery were used to assess relative mortality differences between different regions and different levels of puerulus settlement in the same region. The conclusion from this analysis was that if pueruli are to be harvested in the future, that:

(i) because of the different contributions to the fishery made by pueruli settling three and four years before recruitment in different regions, and

(ii) because of differences in stock dependent mortalities in different regions,

that these factors would need to be taken into account in establishing future harvesting procedures for the fishery.

Because of constraints on time and resources, it was not possible to undertake a study of all areas of the fishery. However, data were available to permit examination of the 29°S – 30°S area to examine the potential for puerulus harvesting. These latitudes encompass the area between Dongara and Geraldton, which is near the centre of the Western Rock Lobster Fishery.

An estimate was made of the rates of survival between settlement of the pueruli and that time that they become legal sized and therefore available to the fishery in this area. It indicated that pueruli and post pueruli are subject to very high mortality, particularly in the first year after settlement. Mortality estimates in the first year were as high as 97-98%, and at least 80-84%. If, for example, it was decided to permit the harvesting of 20 million pueruli from the 29°S – 30°S latitude area, in a year when puerulus settlement was average (i.e. 600 million pueruli settling in this area), and it was deemed desirable to reduce pot numbers to compensate for these puerulus removals, it would be necessary to remove approximately 1% of the number of pot fishing days (i.e. fishing effort) in the 29°S – 30°S latitude area to achieve biological neutrality. This converts to a reduction in fishing effort of approximately 100 pots or 23,000 potlifts for the season.

Methods were investigated to catch large numbers of pueruli. This work showed that the pueruli are easiest to catch near the shore (depths <5m), and in locations with protective fringing reefs.

At Seven Mile Beach we tested (i) a type of puerulus collector, termed a sandwich collector, at different depths and distances offshore, (ii) different collector designs, (iii) the effect of collector size, and (iv) the effect on the catch of the frequency of servicing the collectors. Five collector designs were set in the shallows, two of which had replicates of three different sizes. All were checked over four lunar months during peak settlement in 2000/2001. Sandwich collectors had significantly better catch rates than other collectors and settlement rates were highly correlated with the collector size. Daily servicing for seven days around the time of the new moon, yielded catches 170% higher than those obtained from a single monthly servicing. Thus, results indicate that tests for collectors must take into account the effects of neighbouring collectors on individual collector catches. To do so necessitates that collectors be set out in an array, comprising a matrix of collectors in rows and columns.

The effect of collector position on localized pueruli catch rates was tested at Seven Mile Beach. Pueruli collectors set along a 3 km stretch of coastline at Seven Mile Beach did not show a uniform linear trend in variation in catch rates in a longshore direction, but neighbourhood effects were shown to exist between individual collectors. Some of the longshore collector sites tended to consistently perform better

than others, indicating that in addition to the macro environmental factors that influence pueruli collector catch rates, there are likely to also be localized effects.

Other western rock lobster pueruli harvesting methods were trialled. Neither fixed nets (plankton nets which are set in a fixed position to face prevailing water currents), pump nets (benthic nets which produce a jet of current to expose shallow sand-burrowing fauna), or mid-water trawling, proved to be effective methods for catching pueruli in quantity.

Studies of southern rock lobster (*Jasus edwardsii*) were carried out in Hobart, Tasmania, by the Tasmanian Aquaculture and Fisheries Institute (TAFI), using both Mills (a type of collector designed in Tasmania) and sandwich collectors. Both collectors caught pueruli, but sandwich collectors were shown in this study to achieve high catch rates when deployed on the seafloor. For the considerable advantages of sandwich type collectors to be utilised, a cost-effective method of manufacture will need to be devised. The use of rope hung at mid-water depth levels (midwater longlines) for deploying mesh collectors proved unsuitable, with low catch rates.

Some pueruli of *Jasus edwardsii* emigrate from the Mills collectors after settlement and yield was shown to be greatest when the collectors were serviced at intervals of one week or less. Some pueruli were lost during the hauling of collectors from the seafloor to the boat, with some escaping whilst being hauled to the surface and others being washed from collectors as they were hauled clear of the surface. The use of a scoop net to lift collectors into the boat would reduce this loss, and avoid the complication, and expense, of bagging collectors on the seafloor.

Although it is unlikely that the catch of *J. edwardsii* pueruli per collector will increase substantially with other alternative collector types, collection costs per puerulus might be significantly reduced. This would mean it would be economically viable to deploy greater numbers of collectors, resulting in an increased total puerulus catch.

Commercial collection of southern rock lobster pueruli for aquaculture has already commenced in Tasmania, and the Rock Lobster Industry Advisory Committee in Western Australia stated in March 2001, that the project paves the way for a small scale commercial pilot operation collecting puerulus from the northern zone of the fishery for grow out (the on-growing of pueruli to a marketable sized lobster).

KEYWORDS puerulus, harvest, biological neutrality, *Panulirus cygnus*, *Jasus edwardsii*, puerulus collector, mortality.

Background

The high dollar value of rock lobsters has made them an interesting prospect for aquaculture and has resulted in numerous reviews being written on this subject (*inter alia* van Olst *et al*. 1980, Provenzano, 1985 and Kittaka and Booth, 1994). A major stumbling block in realising the aquaculture potential of these animals has been the difficulties of rearing the larvae through their long and complicated pelagic stages. Though a number of species have been successfully reared through their larval life, (Kittaka, 1994), the production of large numbers of postlarvae has not yet been possible.

In contrast to the difficulties experienced in culturing spiny lobster larvae, the post larvae are relatively easy to rear and numerous authors have reported on the potential for their on-growing to marketable size (*inter alia* Tholasilingam and Rangarajan 1986, Phillips 1988, Meagher 1994, Booth and Kittaka 1994 and Phillips 1997). Good markets, particularly in Japan, exist for small lobsters and it is this market that would initially be targeted by those contemplating the harvesting and culturing of spiny lobster puerulus. This is particularly the case for western rock lobster as they are indistinguishable from *P. japonicus*, the local Japanese lobster which receives a premium price in the Japanese market.

It is not unreasonable to predict that if techniques were developed and put in place to catch large numbers of pueruli and ongrow them, that western lobster production could increase substantially, leading the value of the fishery to possibly double from its present $390 M p.a. to $780 M p.a in the long term. If these techniques were applicable to other Australian spiny lobster species this could increase the value of the national lobster catch from around $450 M p.a. to $900 M p.a..

To allow such additional harvesting from these very valuable fisheries, there are a number of management policy issues that will need to be resolved before the capture and use of wild puerulus for on-growing can be contemplated. The Rock Lobster Industry Advisory Committee (RLIAC) established a Puerulus Enhancement Working Group during 1995. That Working Group employed Dr Bruce Phillips as a consultant, to develop a draft plan that would assist in formatting a future puerulus management policy and research strategy (Phillips 1997). Fishers were updated during the 1997 Rock Lobster Coastal Tour as to the current status of the policy development and the impending submission of this research proposal.

The need for research on the subject of rock lobster aquaculture is recognised and supported by industry and management representatives. In Western Australia these have been identified (Phillips 1997) and are currently being addressed by the RLIAC/(Management Advisory Committee) and the Fisheries Department, which has developed a draft policy document designed to provide the basis for necessary legislative changes, while protecting the existing commercial fishing rights of the rock lobster fishers. There is also a pressing need for initial research on the availability and feasibility of harvesting pueruli for ongrowing, and this forms the basis behind the objectives of this research project.

Western Australia has had a long history of puerulus research, and spatial and temporal fluctuations in the recruitment of *P. cygnus* pueruli to inshore coastal areas of W.A. shores are well understood. A long ongoing project, which now has over 30 years of annual puerulus settlement indices across the W.A. coast, has formed the basis of techniques which are being used to successfully predict future commercial catches three to four years ahead of the event (Phillips 1986, Caputi *et al*. 1995). Good understanding of the puerulus stage of *P. cygnus* makes research facilities in W.A. ideal candidates to develop methods for large-scale harvesting of pueruli and obtain a better understanding of the mortality rates during that phase of the life cycle of the lobster.

This report covers a number of different research aspects and has therefore been presented as a series of chapters, each dealing with a particular research aspect:

Chapter 1 Deals with the question of biological neutrality and the effect large scale harvesting of pueruli might have on the wild fishery for *Panulirus cygnus*.

Chapter 2 The commercial puerulus collector trials for the southern rock lobster *Jasus edwardsii* in Tasmania.

Chapter 3 Deals with the large scale harvesting of pueruli for the western rock lobster fishing for *P. cygnus.*

Chapter 4 Discusses alternative pueruli harvesting methods trialled.

Chapter 5 The effect of collector position on localized western rock lobster puerulus catch rates at Shark Bay and Seven Mile Beach, Western Australia.

Chapter 6 Provides protocol for catching large numbers of pueruli and post pueruli for both *P. cygnus* and *J. edwardsii*

Need

Before any large scale commercial ongrowing of postlarvae is permitted, it will be necessary to establish what effect large-scale harvesting of pueruli might have on the wild stock. A second critical need to the success of any commercial venture into spiny lobster postlarval growout, is that techniques be developed to harvest large quantities of healthy pueruli. Research is needed to estimate the likely impact of large scale harvesting of puerulus on the wild fishery and to establish methods and equipment necessary to catch large quantities of pueruli in the most cost effective way.

Objectives

a) To determine appropriate puerulus to legal size survival rates and potential harvesting ratios, that if implemented in the western rock lobster fishery, might result in 'biological neutrality' being achieved.

b) To establish techniques for large scale harvesting of pueruli for rock lobsters.

1. CHAPTER 1
Examining the question of Biological Neutrality

This chapter gives the summary on the work conducted under this part of the FRDC Project 98/302 report examining the question of biological neutrality. The component report as submitted to the Rock Lobster Enhancement and Aquaculture Subprogram Steering Committee is now Chapter 1 and it details all areas investigated.

Background

The study brief of this component of FRDC Project 98/302 was to examine the impact of puerulus exploitation on the future catches in the wild fishery, and to determine management measures required to maintain 'biological neutrality'. This study was made using existing data on puerulus settlement, juvenile densities and mortalities, and recruitment rates of the western rock lobster. These data have been examined to assess the likely effects on the wild fishery that might result from harvesting pueruli for aquaculture purposes.

It was not possible within the available time frame and resources, to undertake a study of all areas of the western rock lobster fishery (Figure 1). However, data were available to permit examination of the 29°S – 30°S area to test the potential for puerulus harvesting. These latitudes encompass the area between Dongara and Geraldton, which are near the centre of the Western Rock Lobster Fishery. In 1998/1999, a total of 198 different boats fished between the latitudes of 29°S – 30°S for a total catch of 2,375 t.

Any exploitation of the early life history stages of an animal would be expected to result in some, though probably not proportional, change to the number of animals surviving to larger sizes. With this in mind, we have taken the approach in this study of modelling the likely effect on future wild catches that might be predicted to result from the removal of various proportions of the settlement.

A primary aim of sustainability in the Western Rock Lobster Fishery is to maintain the reproductive capacity of the breeding stock at a level sufficient to replenish itself. Biological neutrality is in this context, the level of catch that would need to be forgone to compensate the reproductive capacity of the breeding stock if pueruli are removed for aquaculture. It is not possible to follow the pueruli from settlement right through to the breeding stock. Therefore we have assumed that adjusting the catch to compensate for removals of pueruli for aquacultural purposes would provide sufficient protection of the breeding stock. With the expected age of maturity for lobsters in the Dongara region (the region chosen to examine the question of biological neutrality) being 6.5 years of age, the fishing effort each season must be reduced so that the number of 6.5 year olds under puerulus harvesting is the same under the normal conditions of no puerulus harvesting with normal (no reduction in) fishing effort.

The work covered by this component of FRDC Project 98/302 is reported on in four parts, namely:

1) catch-puerulus relationships;
2) estimating mortality between pueruli settlement and recruitment to the fishery;
3) puerulus mortality model development; and

4) integrating the detailed modelling work in parts 1-3 and discussing the potential application of the models in estimating levels of puerulus exploitation and their likely effects on catches in the fishery.

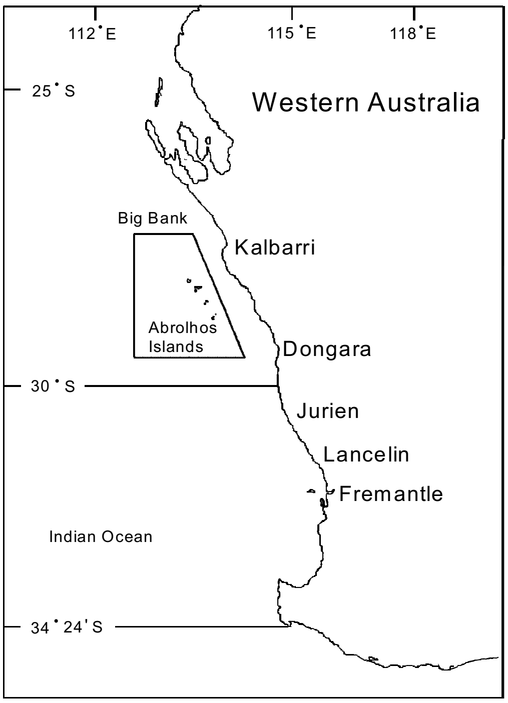

Figure 1. Map showing the main localities along the Western Australian coast at which western rock lobsters are

Figure 1. Map showing the main localities along the Western Australian coast at which western rock lobsters are fished. The Abrolhos Islands are referred to as zone A, zone B is the region north of the 30'th parallel and zone B, the area south.

1.1 Catch-puerulus relationships

1.1.1 Introduction

Catch-puerulus relationships in the western rock lobster were used to assess relative mortality differences between different regions and different levels of puerulus settlement at the same region. As the catch-puerulus relationship is not a straight-line relationship, there is density-dependent mortality occurring between these life history stages and this varies significantly between regions (Caputi *et al.* 1995a). Thus these predictive relationships were used to provide insight into the relative mortality at different levels of abundance of puerulus settlement.

For clarity, the age of a lobster is taken as 0 at hatching from the egg. It is estimated to be approximately 1 year of age at settlement into the coastal reefs as a puerulus stage. It takes 3, 4 or 5 years from the time of settlement as a puerulus before it reaches legal-size. Hence these lobsters are 4, 5 or 6 years of age at recruitment to the fishery. The average time of recruitment is taken as 4.5 years in this report. However, more accurate estimates are made in several sections of the report.

1.1.2 Data

Data on catch and effort for the fishery are available from fisher logbooks and compulsory catch and effort returns. Information by year, month, and degree of latitude is available from the 1967/68 season. Due to the management policies introduced during the 1992/93 season we have omitted post 1992/93 data from consideration so as not to concern ourselves with the effects of the new policy. However, we have decided to use the catch and effort data of 1992/93 since the new policy was introduced during this period and hence, its full effects would not be evident in this data. Catch and effort data have been separated into two seasons. The first, from November to January, is known locally as the whites season, due to the predominance of pale-coloured lobsters in the catch. The second, from February to June is known as the reds season, due to the darker reddish colouring of most of the lobsters caught during this time. Due to the shorter season at the Abrolhos Islands compared to the coast (March-June), the Abrolhos only has a reds season. The information from all collectors has been used. Fishing effort has been given in millions of pot lifts.

Puerulus collector catch information is available by location and month. Data are available from 1968, but only the collectors at Jurien, Dongara and Abrolhos have information for periods longer than 15 years.

1.1.2.1 Mathematical models

There are three common models used to describe the rate of change of an exploited fish population, assuming it is a single cohort population. In further discussions will refer to the number of lobsters remaining at time *t* from a puerulus settlement of a particular settlement season.

Direct density dependent model (Beverton and Holt, 1957)

If the population at time t is N_t, then: $$\frac{dN_t}{dt} = -M N_t$$

where M is termed the instantaneous coefficient of natural mortality.

This model is the most popular one used in fish stock assessment because it is simple, and because data are usually not available to support more complex representations, and because it often makes reasonable assumptions for the exploited age classes.

Stock density dependent mortality model (Harris, 1975)

If M is proportional to the original stock N_0, then: $$\frac{dN_t}{dt} = -(M_s + q_s N_0) N_t$$

where N_0 is the original stock at time zero, and M_s and q_s are constant.

Density dependent mortality model (Harris, 1975)

If M is proportional to the density at time t, then: $$\frac{dN_t}{dt} = -(M_d + q_d N_t) N_t$$

where M_d is the asymptotic mortality when N_t approaches to zero and q_d is the density dependent mortality, which is assumed to be constant. This model is investigated in Section 3 so as to give approximate resolutions to defects that are evident in the models that have been simulated in this section.

1.1.2.2 Previous studies

The present approach differs from the method used in studies that have been published on this subject by Caputi *et al*. (1995a, 1995b, 1996), which were based on the work of Phillips (1986).

Phillips (1986) and then Caputi *et al*.(1995a) predicted western rock lobster catches using indices of puerulus abundance. When using the puerulus index only, the catch for year t was deemed to be related to the abundance of pueruli for years $t - 3$ and $t - 4$ by the following type of relationship:

$$C_{t,t} = aP^{b}{}_{(t-3,\, t-4),\, i} \tag{1.1}$$

where $C_{t,\,i}$ is the catch at year at t location i, and $P_{(t-3,\, t-4),\, i}$ is an average of the annual pueruli collection for years $t - 3$ and $t - 4$ at location i. The parameters were determined by using linear regression after applying a logarithmic transformation to the available data.

We also analysed a similar model termed a "Power Regression", given by:

$$C_{t,t} = aP^{*b}{}_{t,\, i} \tag{1.2}$$

where:

- it is assumed that fishing effort is constant from year to year and that catch can be determined without error;
- a and b are to be determined by a non-linear regression, such that $a > 0$ and $0 \leq b < 1$; and
- $P^{*}{}_{t,\,i}$ is an index of the abundance of pueruli at location i, given by $P^{*}{}_{t,\,i} = \alpha_{t-3}P_{t-3,}\, i + \alpha_{t-4}P_{t-4,}\, i + \alpha_{t-5}P_{t-5,}\, i$, with $(\alpha_{t-3},\, \alpha_{t-4},\, \alpha_{t-5})$ to be determined such that $\alpha_{t-3} + \alpha_{t-4} + \alpha_{t-5} = 1$. The α_{t-j} estimate is a relative weighting of the contribution to year t total catch made by a cohort that settled j years prior, allowing for the natural mortality that occurs prior to recruitment at each age. It is assumed that lobsters which settled 3, 4 and 5 years prior to a particular fishing season, wholly comprise that years total catch.

If equation (1.2) is rewritten as:

$$C_{t,\,i} = aP^{*}{}_{t,\,i}P^{*b-1}{}_{t,\,i} \tag{1.3}$$

then $aP^{*}{}_{t,\,i}$ is related to the total number of pueruli at location i, where a is the product of three confounding parameters (the proportionality constant, the density independent mortality rate, and the fraction of the total number of legal size individuals that actually get caught) and $P^{*b-1}{}_{t,\,i}$ is the stock density dependent mortality rate at location i.

It was not possible to derive a model of this form from first principles (for example as the solution to a first order differential equation as in the Ricker stock recruitment relationship (Hilborn and Walters, 1992)).

Defects of this model include:

- it ignores the residuals in catches of previous years e.g. a higher than predicted catch in one year may lead to a lower than predicted catch in the following year due to the previous catch unexpectedly drawing lobsters from the next year's catch (e.g. due to an abnormally higher recruitment rate to the fishery during that year);
- predicted catch is unbounded in that as $P^*_{t,i}$ increases so too does the predicted catch. Due to puerulus survival numbers being dependent on the amount of suitable habitat, however, we should expect that as the puerulus index $P^*_{t,i}$ increases, the predicted catch should approach some asymptote; and assumes that the fishing effort is constant from season to season.

1.1.2.3 Alternative model

The alternative model examined takes the form of a Ricker stock recruitment relationship equation (Hilborn and Walters, 1992):

$$C_t = a \times P^*_t \times e^{-b * P^*_t}, \tag{1.4}$$

where P^*_t is the puerulus index, a has the same properties of the previous model, while b is the relative increase in mortality associated with each unit of the puerulus index measure. The power term can be modified to more closely reflect the stock density dependent response of mortality to puerulus density.

This model has a contrasting deficiency to the previous one, in that it predicts an increase in catch for an increase in puerulus index until a certain level of puerulus index, when it then predicts a decrease in the level of catch for any further increase in puerulus index. Catch data experienced in reality however, are contrary to this behaviour in that as $P^*_{t,i}$ increases so too does the predicted catch. For reasons discussed previously however, we should expect that the predicted catch should approach some asymptote. This model then has the same remaining defects as the previous one. The assumption of constant fishing effort however, can be overcome to some degree by the adjusted model:

$$C = aP^*_{t0}e^{-bP^*_t + s\,\ln E} \tag{1.5}$$

where a, b, and P^*_{t0} are defined as previously, E denotes the effort (number of pot lifts in millions) and s determines the proportion of effort that contributes to the catch. This model however, is probably only adequate when effort and exploitation are small.

Derivation of the Ricker-related Pueruli Catch model

Let $N_{t0}(t)$ represent the number of individuals in a band, t seasons after the settlement of the youngest members. *Band* in this sense is used to refer to the individuals that have settled during the seasons $(t_0 - 2)$, $(t_0 - 1)$ and t_0 and will provide the lobsters for the fishing season of year $t = (t_0 + 3)$. Note that we are making the simplified assumption that puerulus settlement in a given season is independent of puerulus settlement in neighbouring seasons and that survival is only dependent on the number of individuals in the band. We claim that the number of individuals in a band is proportional to puerulus settlement in the following way:

$$N_{t_0}(0) = \rho P_{t_0}^*, \tag{1.6}$$

where ρ is a proportionality constant, and P_{t0}^*, the puerulus index, is defined by:

$$P_{t_0}^* = \alpha_1 P_{t_0} + \alpha_2 P_{t_0 - 1} + \alpha_3 P_{t_0 - 2} \ . \qquad (1.7)$$

The sum of the weightings $(\alpha_1, \alpha_2, \alpha_3)$ for the three puerulus settlement values is equal to 1. α_i is the relative weighting that a cohort which settled in year $t_0 - i + 1$ makes to $N_{t0}(0)$, allowing for the natural mortality that occurs prior to recruitment at each age.

We propose an ordinary differential equation of the Ricker form (page 260 Hilborn and Walters, 1992):

$$\frac{dN_{t_0}(t)}{dt} = -(M_s + q_s \rho P_{t_0}^*) N_{t_0}(t) \,, \qquad (1.8)$$

where $M_s + q_s \rho P_{t0}^*$ is the instantaneous mortality of the band, M_s is the constant for the direct density independent mortality rate, and q_s is the stock-density dependent mortality coefficient, that is, the mortality at time t is dependent on the puerulus index P_{t0}^*. Then it follows that the population at time t is:

$$N_{t_0}(t) = N_{t_0}(0)\, e^{-(M_s + q_s \rho P^*_{t0})t} \,. \qquad (1.9)$$

This leads to the solution:

$$\begin{aligned} N_{t_0}(t) &= N_{t_0}(0) e^{-M_s t} e^{-q_s \rho^*_{t0} t} \\ &= \rho P^*_{t_0} e^{-M_s t} e^{-q_s \rho P^*_{t0} t} \end{aligned} \qquad (1.10)$$

Here $e^{-M_s t}$ is independent of the stock and the density at time t, and $e^{-q_s \rho P^*_{t0} t}$ depends on the number of lobsters in the band at time t_0.

For a given year t, the catch is related to the band of individuals N_{t-3} (grouping other factors into constants) by:

$$C(t) = \beta N_{t-3}(3) = a P^*_{t_0} e^{-bP^*_{t0}} \qquad (1.11)$$

where β is the fraction of individuals in the band that are actually caught, multiplied by the average weight of a legal sized individual in kilograms.

The parameters a and the stock-density dependent coefficient b are defined by:

$$\begin{aligned} & a = \rho\beta e^{-M_s t} \text{ and } b = \rho q_s t \\ & \Rightarrow \rho = \frac{a}{\beta e^{-M_s t}} \text{ and } \rho = \frac{b}{q_s t} \\ & \Rightarrow \frac{a}{\beta e^{-M_s t}} = \frac{b}{q_s t} \\ & \Rightarrow q_s = \frac{b}{a}\left(\frac{\beta e^{-M_s t}}{t}\right) \end{aligned}$$

For simplicity it is assumed that M_s and t are constant, which implies $\left(\frac{\beta e^{-M_s t}}{t}\right)$ is constant and hence, q_s is proportional to $\frac{b}{a}$.

A property of this model is that it reaches a maximum catch, and then starts to decline with an increasing puerulus index. However, this potential problem has not resulted, to any extent, with the levels of catch that have been recorded in the past.

1.1.3 Methods

1.1.3.1 Summarising pueruli collector information

The puerulus values used in the calculations were obtained by using the Winsorized mean estimator (Kendall and Stuart 1973) of the puerulus values for each month from all the collectors in a location. The Winsorized mean of an ordered set $(a_1,\ldots,a_n)$ is given by:

$$m_w = \frac{1}{n}[(i+1)(a_{(i+1)} + a_{(n-i)}) + \sum_{s=i+2}^{n-i-1} a_s]. \qquad (1.12)$$

This amounts to replacing the highest ith values in the set with the $(i = 1)$th highest value, and lowest ith values with the $(i + 1)$th lowest, and then taking the arithmetic mean of the resulting set. Since we had only up to six collectors at any one location, we chose to let $i = 1$. This is used as a compromise between the more familiar *trimmed mean*, which simply removes the highest and lowest ith values before taking the mean, and the arithmetic mean.

The Winsorized mean is a more appropriate method to standardise the treatment of regions, for example where new collectors may have been added during the data collection period. This is so for the following reasons. Firstly, for a normally distributed sample, the Winsorized mean estimator has "99.9 per cent efficiency compared with the MV (minimum variance) unbiased linear estimator" (Kendall and Stuart, p. 544). Secondly, if the new collector has significantly better or worse collection properties, then it will automatically be removed from the analysis by the Winsorized mean. Hence it is more stable that the arithmetic mean.

The data used in this study contain different numbers of collectors in different years, hence the need for the Winsorized mean, whereas previous studies (Caputi *et al.*, 1995a) used the same collectors throughout the study period, even though more collectors were added at some of the sites. Initially, the only collectors considered have been those at Jurien and Alkimos for Zone C (the southern part of the fishery), Dongara for Zone B (the northern part of the fishery) and Abrolhos Islands for Zone A. The Winsorized mean of the monthly collector information was summed over the duration of a puerulus settling season, which has been taken as extending from the end of May to the beginning of April each year, to give the puerulus index value for a complete season of settlement.

1.1.3.2 Non-linear regression

A non-linear regression model attempts to find the parameters β, so that the function $\eta(\beta,x)$fits the given data vector y as closely as possible, where:

$$y = \eta(\beta,x) + \varepsilon \qquad (1.13)$$

In our situation, is the vector of annual catch information for a given region, x is the puerulus index (as defined above) over the seasons between 1968 and 1992, and $\eta(\beta,x)$ is the model of the catch information with parameters β, and ε is normally distributed. We should note that in analysis performed for the Abrolhos Islands, catch years 1982-1987 have been omitted due to the absence of collector information for puerulus settlement during these years.

When comparing models of a given data set that use varying numbers of parameters, the AIC criterion (Equation 1.14) is commonly used to select the most appropriate model. It provides a trade off between the cost of using an increased number of parameters, against the improved fit of the model.

$$AIC = n \log(RSS / \mathrm{n}) + 2p \qquad (1.14)$$

where:

n is the number of observation,

RSS is the Residual Sum of Squares, and

p is the number of parameters used by the model.

The quality of the regression fit is indicated by the size of the AIC result, with smaller numbers indicating a better fit than larger numbers.

1.1.4 Results and discussion

In summary, catch by type (total catch of whites and reds) for the years between 1968-1992 that had adequate collector (puerulus) information, were fitted by three different models. With each model and catch type, a simple model was firstly fitted by relating puerulus information 3 and 4 years prior to each particular catch. A more complex model was then fitted using the additional information of puerulus settlement five years prior to each catch.

The results from the Ricker model (Table 1) show the proportion of the catch that is attributable to puerulus settlement at 3, 4, and 5 years prior to recruiting into the fishery as determined by the associated model. Where the data refer to only $t - 3$ and $t - 4$, the proportion of the catch attributable to settlement three years before has been approximately 50%, 40% and 40% in zones A, B, and C, respectively, with the balance of the catch attributable to year 4. Where the data refer to years $t - 3$, $t - 4$ and $t - 5$, the proportion of the catch attributable to settlement three years before is suggested as being approximately 50%, 40% and 40% in Zones A, B, and C, with the balance of the catch mostly in year 4. There was little variation between the results obtained for the model runs that included $t - 5$ in this and other scenarios (Tables 1-5).

Model runs showing the proportion of the commercial western rock lobster catch made in different regions of the fishery, attributable to puerulus settlement 3, 4, and 5 years prior to the season in which the catch was made, have been calculated and are represented graphically for the various catch model equations (Figures 2-9).

Table 1. Total catch of whites and reds combined Model equation (1.4): $C_t = aP^*_{t0}e^{-bP^*_{t0}}$

Collector	Region	α (x10^3)	α_{t-3}	α_{t-4}	α_{t-5}	b (x10^{-2})	AIC	RSS (x10^9)	d.f.
ABR	Zone A	49.3	0.55	0.45	NA	1.02	237.1	108.57	7
		51.5	0.20	0.57	0.23	1.07	209.4	46.94	5
DON	Zone B	96.0	0.41	0.59	NA	0.94	505.3	4913.8	16
	(Whole Region)	97.7	0.36	0.34	0.3	0.97	505.0	4346.2	15
	Zone B	52.1	0.41	0.59	NA	0.80	459.5	748.8	16
	(29°S Transect)	51.3	0.31	0.50	0.19	0.79	468.6	642.2	15
JUR	Zone C	123.3	0.52	0.48	NA	0.76	470.2	1224.8	14
	(Whole Region)	121.6	0.50	0.45	0.05	0.76	472.0	1211.3	13
	Zone C	48.9	0.55	0.45	NA	0.74	425.2	869.6	14
	(30°S Transect)	48.4	0.53	0.42	0.05	0.74	426.9	853.6	13
ALK	Zone C	817.4	0.44	0.56	NA	4.96	156.9	505.8	3
	(Whole Region)	697.2	0.48	0.43	0.09	4.33	154.8	254.0	2
	Zone C	312.8	0.32	0.68	NA	4.06	148.2	118.8	3
	(31°S Transect)	308.0	0.34	0.64	0.02	4.02	149.9	111.3	2

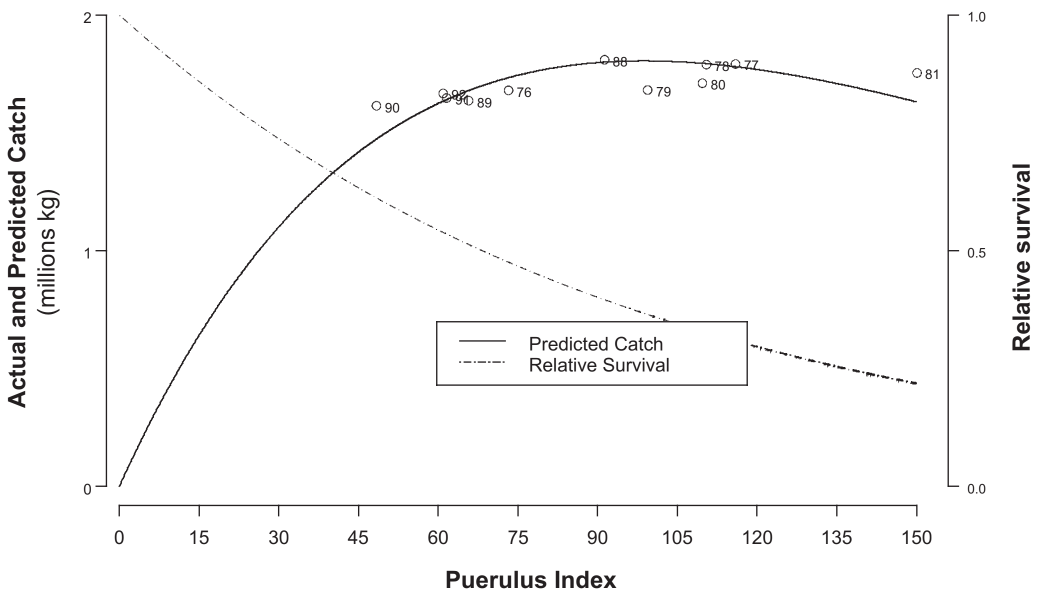

Figure 2. The relative survival of *Panulirus cygnus* versus puerulus index, and the total catch as fitted by the Ricker model, where the puerulus index has been constructed using Abrolhos collector information 3 and 4 years prior to the year of catch in zone A.

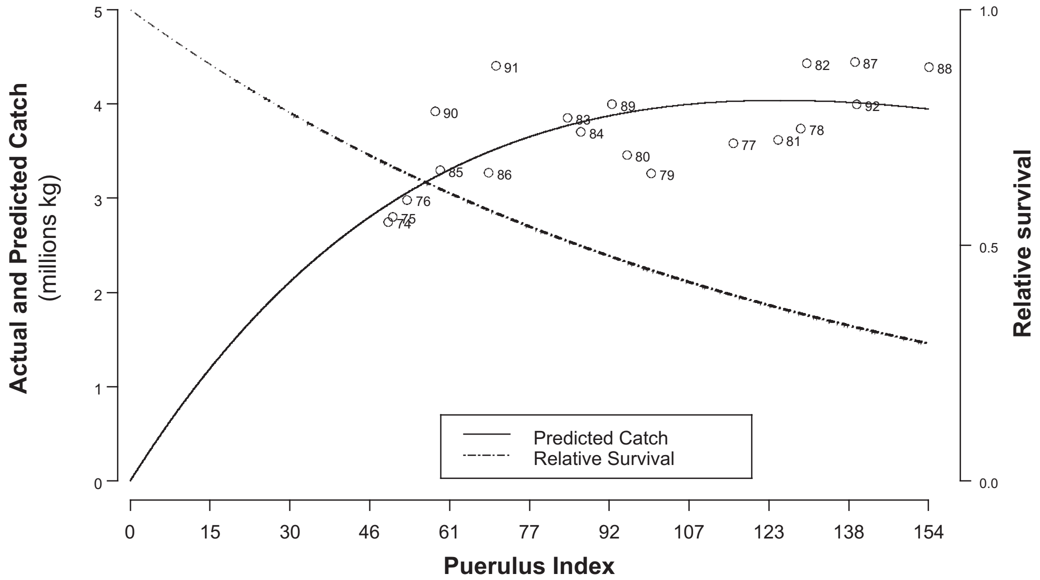

Figure 3. The relative survival of *Panulirus cygnus* versus puerulus index, and the total catch as fitted by the Ricker model, where the puerulus index has been constructed using Dongara collector information 3 and 4 years prior to the year of catch in zone B.

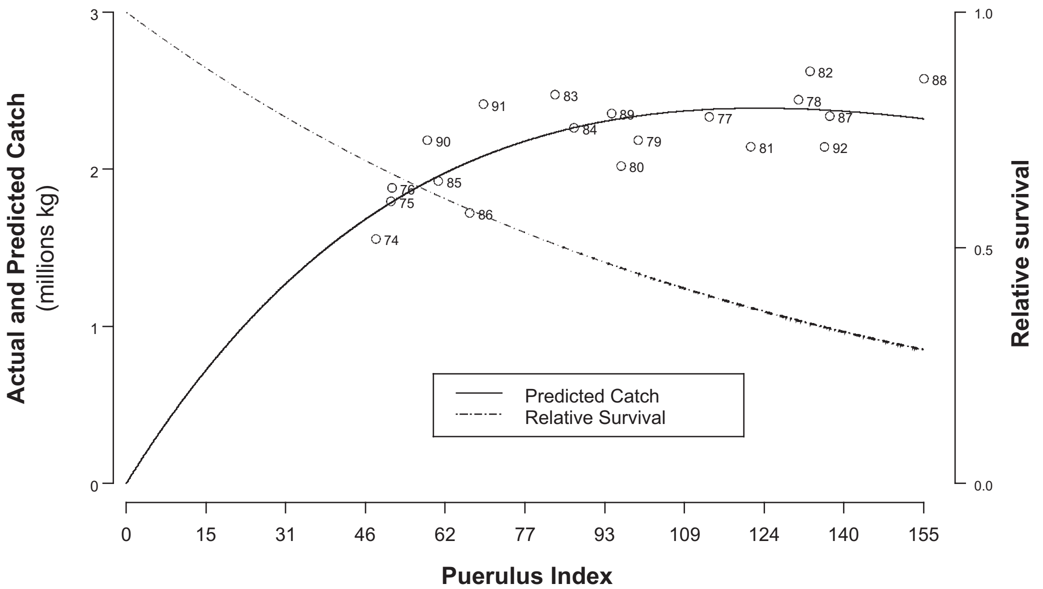

Figure 4. The relative survival of *Panulirus cygnus* versus puerulus index, and the total catch as fitted by the Ricker model, where the puerulus index has been constructed using Dongara collector information 3 and 4 years prior to the year of catch for the transect in zone B.

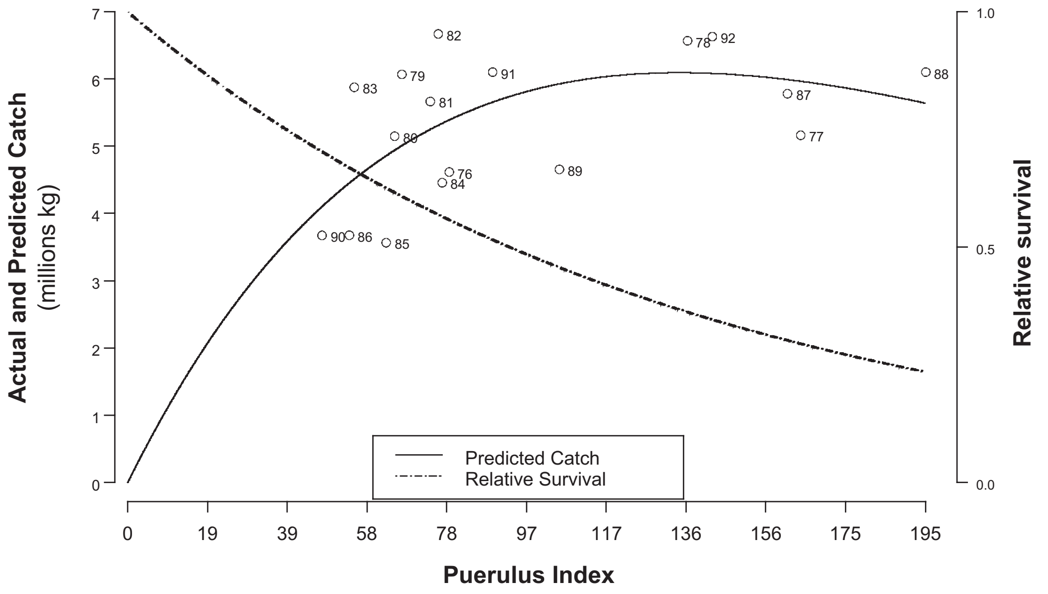

Figure 5. The relative survival of *Panulirus cygnus* versus puerulus index, and the total catch as fitted by the Ricker model, where the puerulus index has been constructed using Jurien collector information 3 and 4 years prior to the year of catch in zone C.

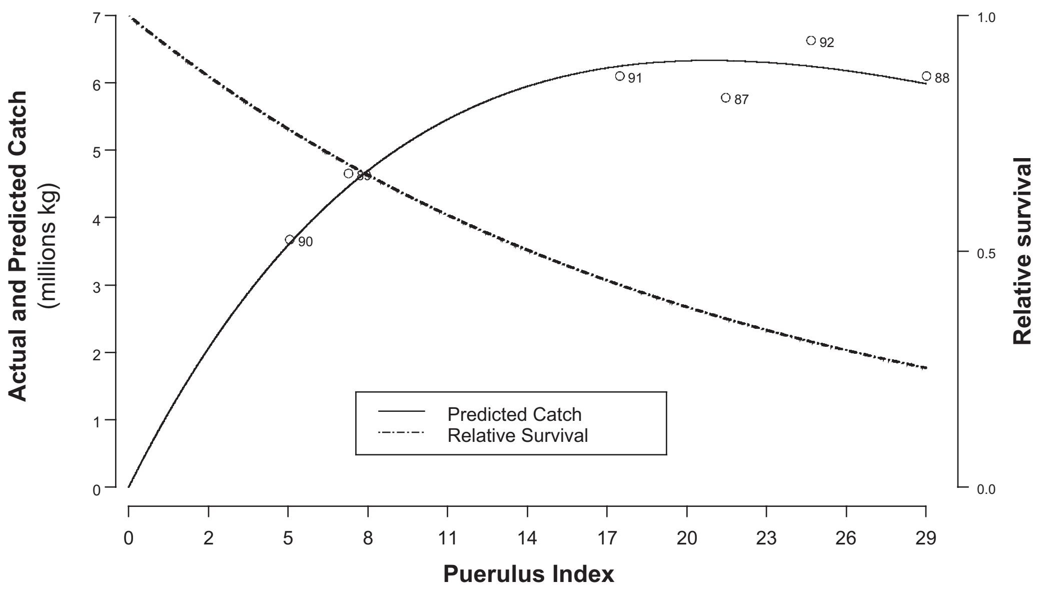

Figure 6. The relative survival of *Panulirus cygnus* versus puerulus index, and the total catch as fitted by the Ricker model, where the puerulus index has been constructed using Alkimos collector information 3 and 4 years prior to the year of catch in zone C.

Table 2. Whites Catch (from November to January). Model equation (1.4): $C_t = aP^*_{t0}e^{-bP^*_{t0}}$

Collector	Region	α (x10³)	α_{t-3}	α_{t-4}	α_{t-5}	b (x10⁻²)	AIC	RSS (x10⁹)	d.f.
DON	Zone B	59.9	0.54	0.46	NA	1.12	493.7	2669.7	16
	(Whole Region)	59.9	0.51	0.35	0.14	1.12	495.3	2607.1	15
	Zone B	27.6	0.28	0.72	NA	0.71	460.0	451.8	16
	(29°S Transect)	26.7	0.17	0.57	0.26	0.67	456.9	345.6	15
JUR	Zone C	64.9	0.34	0.66	NA	0.75	458.1	6011.8	14
	(Whole Region)	63.2	0.30	0.63	0.07	0.73	459.9	5954.4	13
	Zone C	27.0	0.40	0.60	NA	0.74	415.1	480.9	14
	(30°S Transect)	27.1	0.40	0.60	0.00	0.74	417.1	480.6	13
ALK	Zone C	347.3	0.35	0.65	NA	4.20	158.3	634.0	3
	(Whole Region)	249.0	0.39	0.40	0.21	2.66	152.5	173.5	2
	Zone C	142.0	0.18	0.82	NA	3.29	142.0	41.8	3
	(31°S Transect)	13.24	0.22	0.71	0.07	3.06	141.1	25.7	2

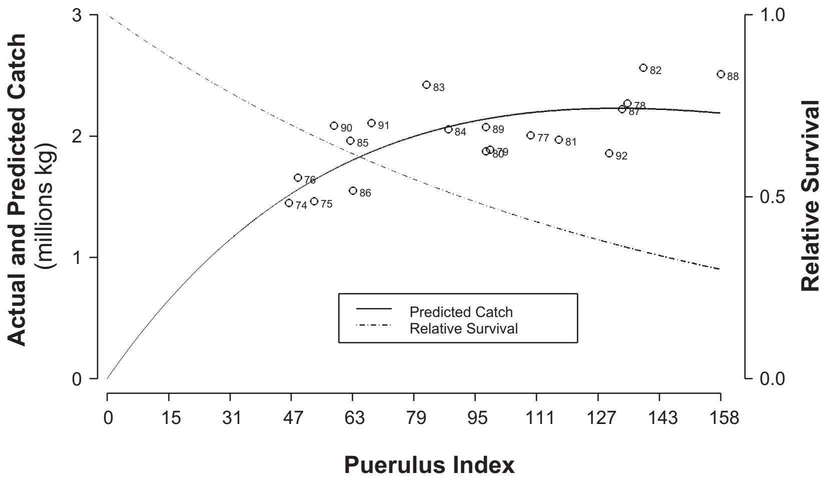

Figure 7. The relative survival of *Panulirus cygnus* versus puerulus index, and the whites catch as fitted by the Ricker model, where the puerulus index has been constructed using Dongara collector information 3 and 4 years prior to the year of catch in zone B.

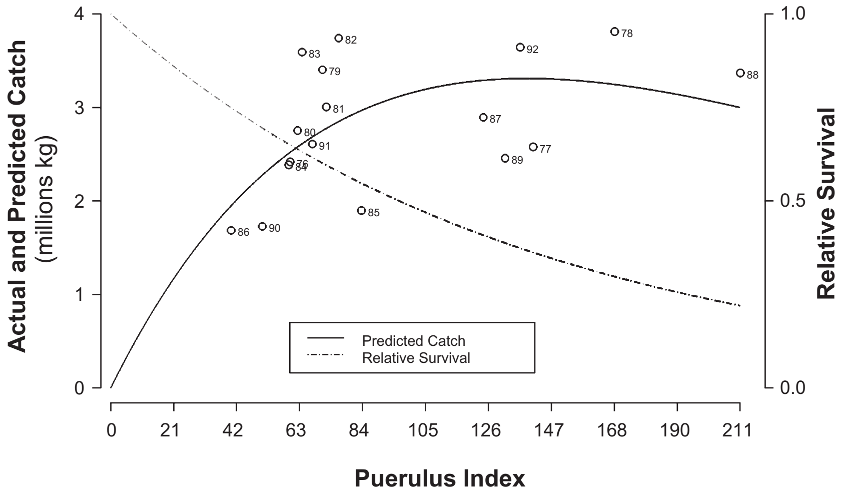

Figure 8. The relative survival of *Panulirus cygnus* versus puerulus index, and the whites catch as fitted by the Ricker model, where the puerulus index has been constructed using Jurien collector information 3 and 4 years prior to the year of catch in zone C.

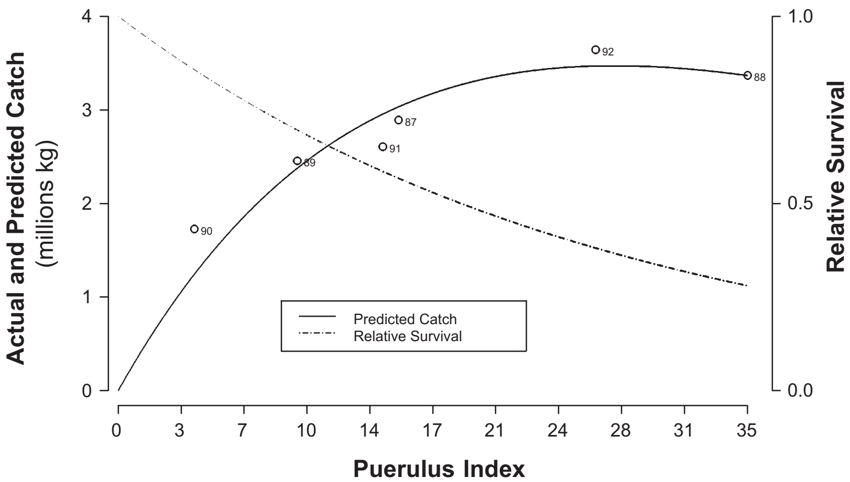

Figure 9. The relative survival of *Panulirus cygnus* versus puerulus index, and the whites catch as fitted by the Ricker model, where the puerulus index has been constructed using Alkimos collector information 3 and 4 years prior to the year of catch in zone C.

Table 3. Reds catch from February to June. Model equation (1.4): $C_t = aP^*_{t0}e^{-bP^*_{t0}}$

Collector	Region	α (x10[3])	α_{t-3}	α_{t-4}	α_{t-5}	*b* (x10[-6])	AIC	RSS (x10[9])	d.f.
DON	Zone B	37.3	0.48	0.52	NA	0.75	484.5	1648.5	16
	(Whole Region)	38.3	0.47	0.28	0.15	0.78	485.9	1594.9	15
	Zone B	24.0	0.49	0.51	NA	0.89	446.9	227.1	16
	(Whole Transect)	24.4	0.46	0.41	0.13	0.92	448.5	223.0	15
JUR	Zone C	56.9	0.68	0.32	NA	0.73	440.7	2165.4	14
	(Whole Region)	56.1	0.66	0.29	0.05	0.73	442.4	2123.9	13
	Zone C	21.3	0.69	0.31	NA	0.71	405.6	274.9	14
	(30°S Transect)	20.4	0.65	0.23	0.12	0.69	405.5	243.4	13
ALK	Zone C	446.0	0.45	0.55	NA	5.31	151.0	187.0	3
	(Whole Region)	697.2	0.48	0.43	0.09	4.33	154.8	254.0	2
	Zone C	180.7	0.45	0.55	NA	4.95	141.7	39.7	3
	(31°S Transect)	329.9	0.13	0.29	0.58	9.47	154.3	234.8	2

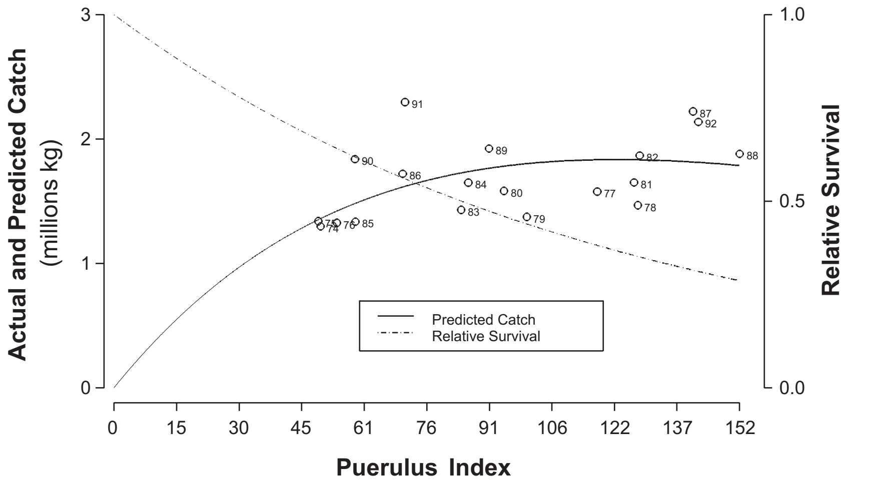

Figure 10. The relative survival of *Panulirus cygnus* versus puerulus index, and the reds catch as fitted by the Ricker model, where the puerulus index has been constructed using Dongara collector information 3 and 4 years prior to the year of catch in zone B.

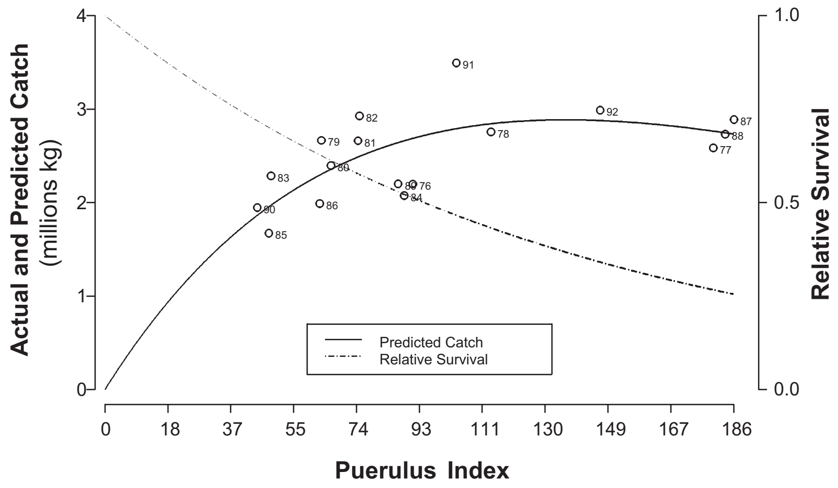

Figure 11. The relative survival of *Panulirus cygnus* versus puerulus index, and the reds catch as fitted by the Ricker model, where the puerulus index has been constructed using Jurien collector information 3 and 4 years prior to the year of catch in zone C.

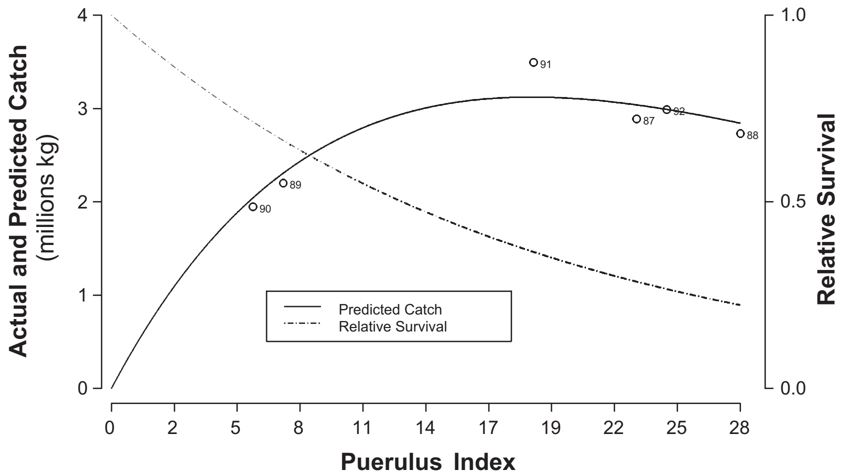

Figure 12. The relative survival of *Panulirus cygnus* versus puerulus index, and the reds catch as fitted by the Ricker model, where the puerulus index has been constructed using Alkimos collector information 3 and 4 years prior to the year of catch in zone C.

Table 4. Total catch of whites and reds combined. Model equation (1.2): $C(t) = aP^{*b}_{t0,\,i}$

Collector	Region	α (x10³)	α_{t-3}	α_{t-4}	α_{t-5}	b (x10⁻²)	AIC	RSS (x10⁹)	d.f.
ABR	Zone A	1182.76	0.89	0.11	NA	9.82	238.08	16.00	8
		1219.22	0.87	0.13	0.00	9.02	240.13	10.08	6
DON	Zone B	1160.25	0.32	0.68	NA	29.82	493.96	2705.54	16
	(Whole Region)	1039.81	0.33	0.66	0.01	29.12	495.97	2707.38	15
	Zone B	722.41	0.16	0.84	NA	17.84	465.74	612.71	16
	(29°S Transect)	586.81	0.17	0.71	0.12	17.14	465.58	546.93	15
JUR	Zone C	1966.01	0.45	0.55	NA	43.64	471.27	13081.95	14
	(Whole Region)	2123.32	0.55	0.44	0.00	42.25	473.85	13534.04	13
	Zone C	817.92	0.53	0.47	NA	17.34	424.67	843.50	14
	(30°S Transect)	899.53	0.67	0.33	0.00	16.55	428.75	953.16	13
ALK	Zone C	2377.57	0.40	0.60	NA	71.09	159.47	770.14	3
	(Whole Region)	1747.25	0.46	0.46	0.08	70.06	161.44	767.17	2
	Zone C	886.26	0.38	0.62	NA	31.28	151.58	206.64	3
	(31°S Transect)	818.10	0.27	0.72	0.01	29.94	156.85	356.44	2

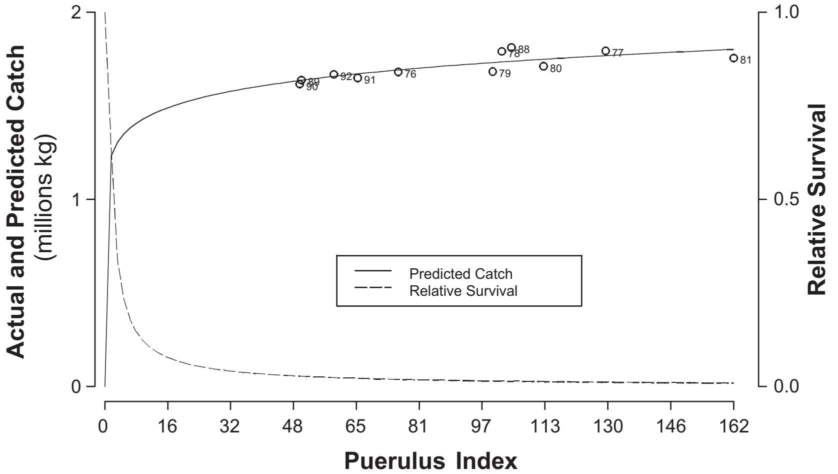

Figure 13. The relative survival of *Panulirus cygnus* versus puerulus index, and the total catch as fitted by the Power model, where the puerulus index has been constructed using Abrolhos collector information 3 and 4 years prior to the year of catch in zone A.

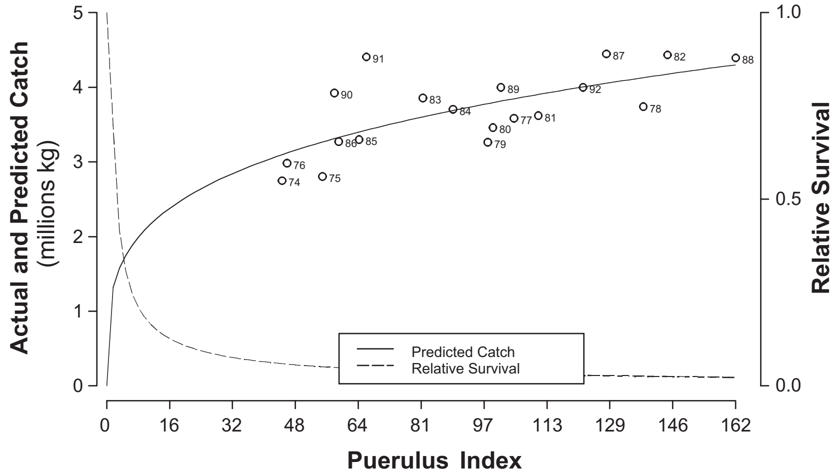

Figure 14. The relative survival of *Panulirus cygnus* versus puerulus index, and the total catch as fitted by the Power model, where the puerulus index has been constructed using Dongara collector information 3 and 4 years prior to the year of catch in zone B.

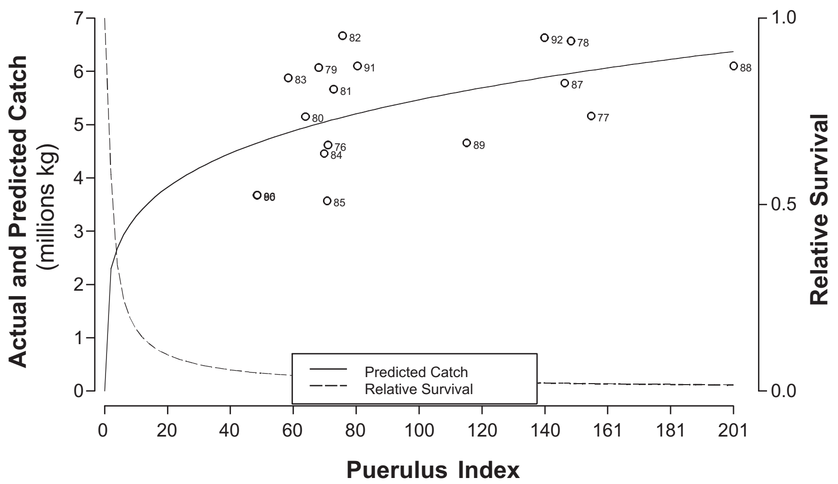

Figure 15. The relative survival of *Panulirus cygnus* versus puerulus index, and the total catch as fitted by the Power model, where the puerulus index has been constructed using Jurien collector information 3 and 4 years prior to the year of catch in zone C.

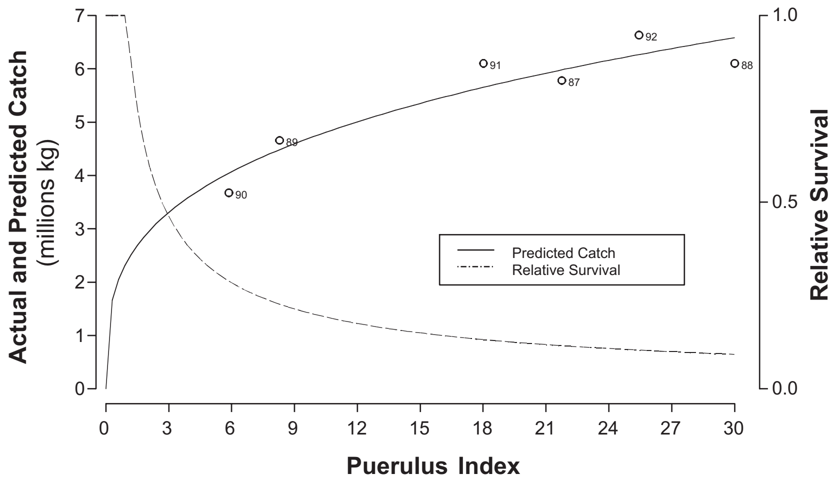

Figure 16. The relative survival of *Panulirus cygnus* versus puerulus index, and the total catch as fitted by the Power model, where the puerulus index has been constructed using Alkimos collector information 3 and 4 years prior to the year of catch in zone C.

Table 5. Total catch of whites and reds combined. Model equation (1.5): $C = aP^{*b}_{t_0, i}$

Collector	Region	α (x10³)	α_1	α_2	α_3	b (x10⁻²)	s (x10-7)	AIC (x10⁹)	RSS	d.f.
ABR	Zone A	32.09	0.68	0.32	NA	0.943	2.59	253.65	54.95	6
		30.17	0.51	0.29	0.20	0.938	2.95	244.19	19.39	4
DON	Zone B	41.91	0.51	0.49	NA	0.855	1.95	480.24	1183.37	14
	(Whole Region)	42.35	0.51	0.48	0.02	0.855	1.92	482.21	1181.53	13
	Zone B	30.94	0.44	0.56	NA	0.795	2.19	465.45	543.10	14
	(29∞S Transect)	34.27	0.40	0.53	0.07	0.792	1.73	467.02	531.03	13
JUR	Zone C	40.72	0.44	0.56	NA	0.786	1.90	442.59	10007.86	12
	(Whole Region)	38.13	0.39	0.55	0.05	0.782	1.99	444.39	9882.39	11
	Zone C	38.23	0.56	0.44	NA	0.749	1.11	402.40	811.74	12
	(29∞S Transect)	38.58	0.54	0.43	0.03	0.748	1.04	404.26	804.59	11

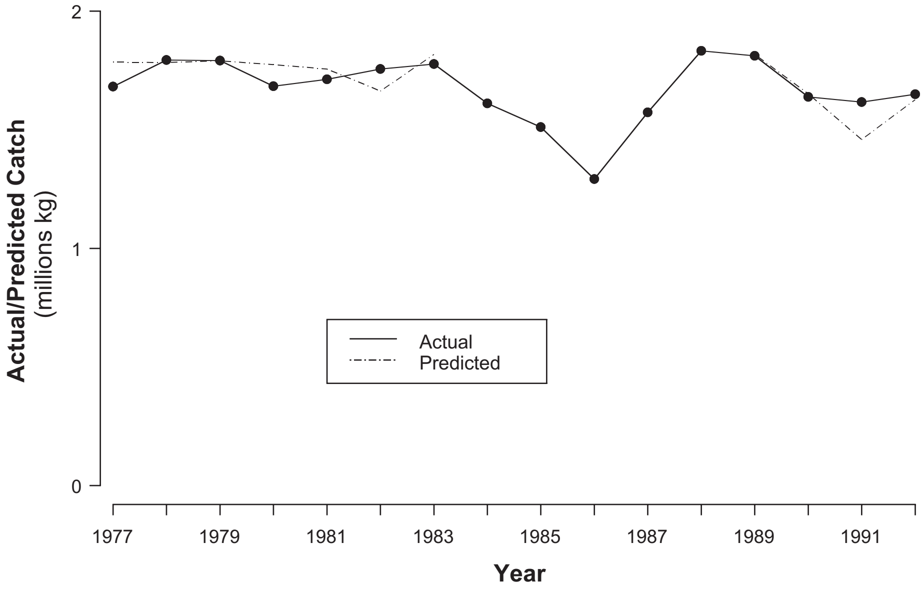

Figure 17. Actual and predicted total catch of *Panulirus cygnus* as fitted by the Ricker model with fishing effort, where the puerulus index has been constructed using Abrolhos collector information 3 and 4 years prior to the year of catch in zone A.

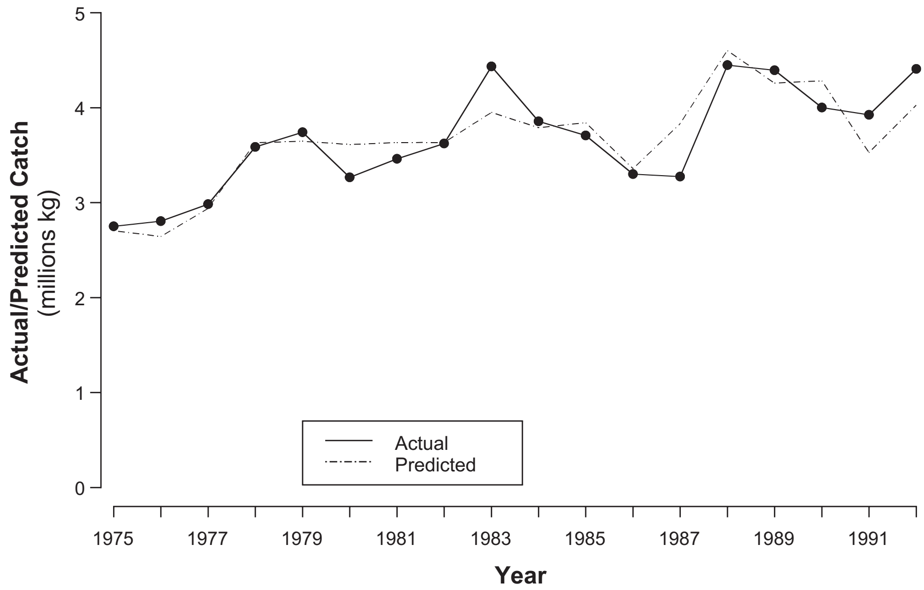

Figure 18. Actual and predicted total catch of *Panulirus cygnus* as fitted by the Ricker model with fishing effort, where the puerulus index has been constructed using Dongara collector information 3 and 4 years prior to the year of catch in zone B.

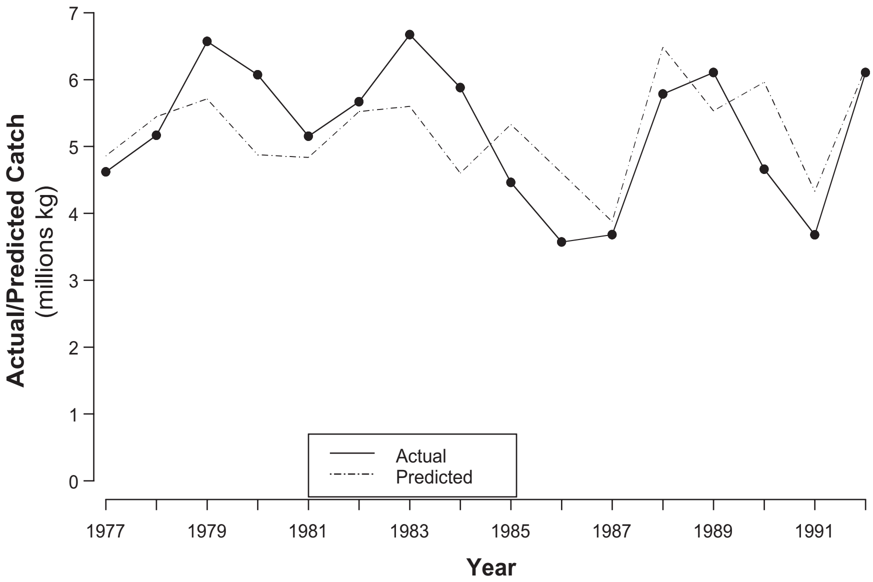

Figure 19. Actual and predicted total catch of *Panulirus cygnus* as fitted by the Ricker model with fishing effort, where the puerulus index has been constructed using Jurien collector information 3 and 4 years prior to the year of catch in zone C.

It is clear from Tables 2 and 3, that there is a very different relationship between settlement at times t - 3, t - 4 and t - 5 and the proportion of the whites and reds catch which was attributable to those settlements. These data, which are only available for the coastal areas, show that the whites catch is generally dependent on settlement four years earlier (Table 2), while the reds catch is more dependent on settlement three years prior to the catch. The reason for this is because most animals take four years from puerulus settlement to recruitment to the fishery. However, a proportion of fast-growing individuals, or those that settled earlier in the season, attain the legal minimum size in a moult that takes place mid-way through the commercial fishing season (in February to April each year) and recruit to the fishery late in the season as reds. Graphs predicting catch and relative survival based on various levels of puerulus settlement are shown for different regions of the fishery for the "whites" catch in Figures 6-8 and for the "reds" catch in Figures 10-12.

The stock-dependent mortality coefficient $\frac{b}{a}$, where b and a are listed in model outputs (Tables 1 to 5), provides assessments of relative stock-density dependent mortality in the fishery. The mortality coefficient results from the model run outputs described in Tables 1 to 3, indicate that there is an increase in relative stock-density dependent mortality in the northern part of the fishery, in particular at the Abrolhos Islands (Figures 20 and 21). This corresponds to those parts of the fishery with the highest densities of lobsters. Similar results have been obtained in previous studies (e.g. Caputi *et al*. 1996).

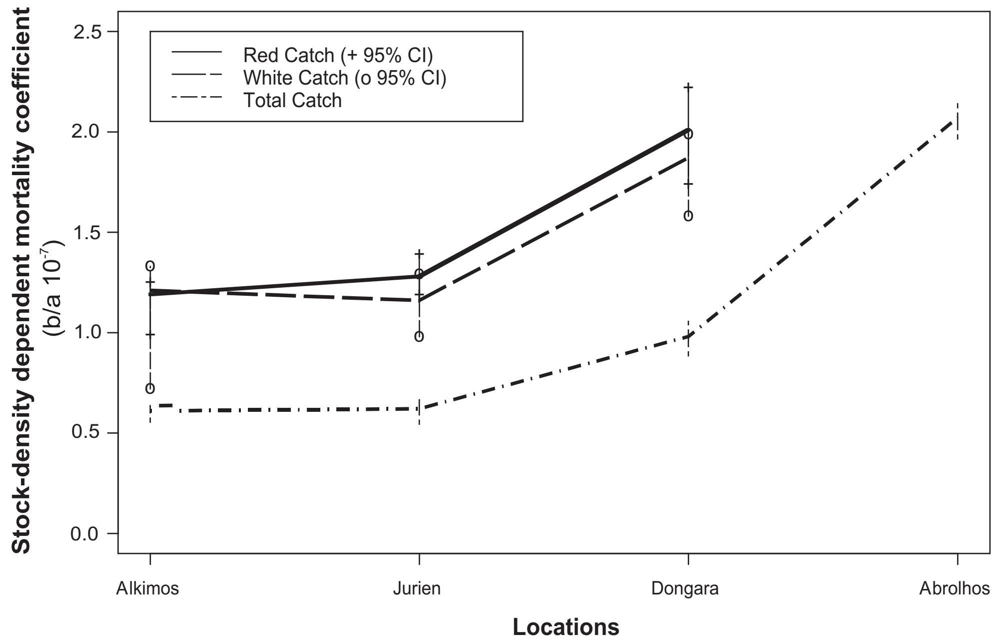

Figure 20. The stock-density dependent mortality (with 95% confidence intervals) for the whole area of each region, for the total, whites and reds catches in each zone.

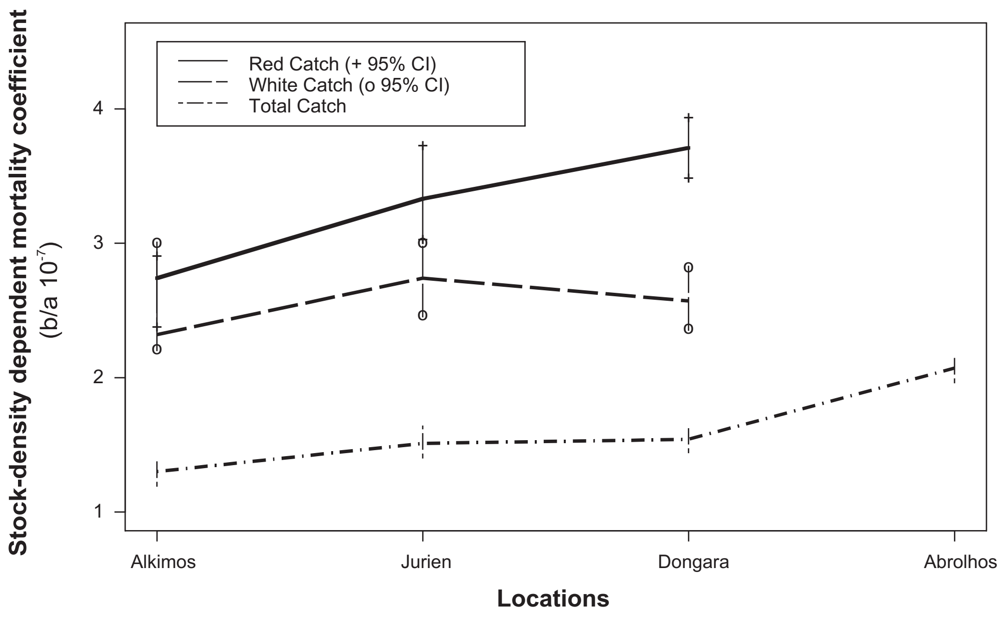

Figure 21. The stock-density dependent mortality for the one-degree transect of each region, for the total, whites and reds catches in each zone.

Figure 20 shows that generally, there is an increasing trend in mortality rates for all categories of lobster (whites, reds, and combined) as the latitudes decrease. The pattern of mortality rate is less clear where single one degree transects have been considered (Figure 21). Although the combined catches indicate that there is a slight trend towards an increasing mortality rate as the latitude decreases, the white and red catches are less consistent. The mortality for the white catches increases and has its maximum at the Jurien transect. For red catches, Alkimos had the lowest mortality, then a slight increase at Jurien, Dongara and the Abrolhos Islands (since the Abrolhos Islands only have a red season (fishing does not commence there till 15 March), the total catch of the Abrolhos Islands is also the reds catch for that zone). The 95% CI in Figures 20-21 were calculated using non-parametric bootstrapping.

Comparing the results of the Ricker model (Hilborn and Walters 1992, page 260) (Table 1) and the power model (Caputi *et al.* 1995a) (Table 4), all estimated parameters are different but the residual sum of squares and AIC criteria are similar. In the Ricker model, is the annual catch per puerulus at low stock sizes when the puerulus index is below 50, and describes how quickly the annual catch per puerulus drops as the puerulus index increases. In the power model, is the annual catch per puerulus at low stock sizes. Both models fit the data reasonably well and can thus be used equally well in making assessments of density dependence. Figure 22 illustrates the similarity between these two functions over their related puerulus index for the 29°S – 30°S region, the region that will be studied more closely in Section 3 when establishing biological neutrality consequences i.e. the required reduction in fishing effort needed to maintain current spawning stock levels if it was decided to allow puerulus harvesting.

Comparisons of Table 1 and Table 5 show all estimated parameter values to be similar. The model used in Table 5, which incorporates effort, has allowed effort parameters to be calculated. The estimates of parameter in Zone A, Zone B and Zone C were 2.59 x 10^{-7}, 1.95 x 10^{-7} and 1.90 x 10^{-7}, respectively.

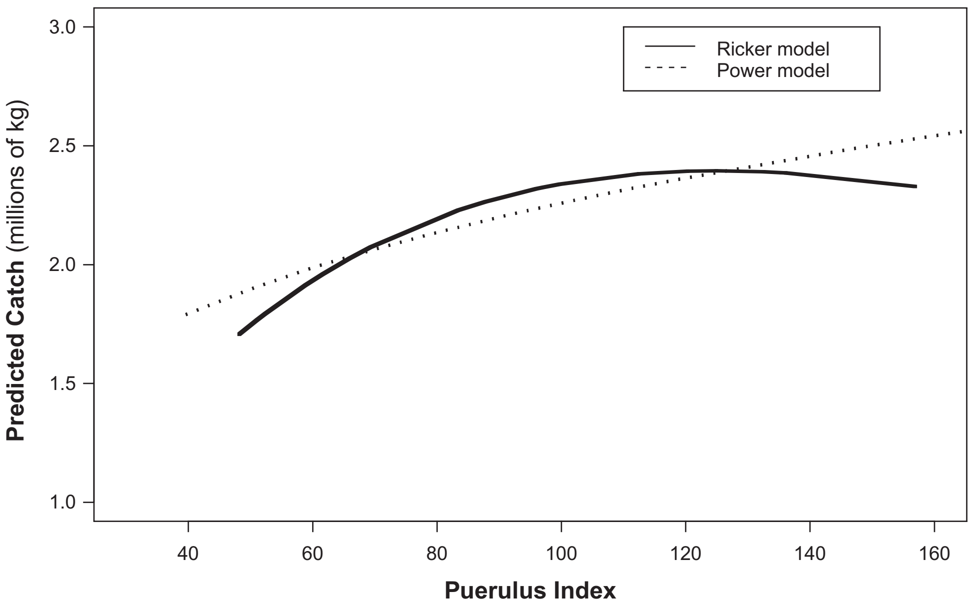

Figure 22. An overlay of the fitted Ricker and Power curves for the total catch data of the 29°S – 30°S transect for the years 1974–1992.

A comparison of the AIC criteria in Table 1 and Table 5 suggests that the Ricker model with effort is a better predictor, than the Ricker model without effort, of the annual catch. The variation of annual catch in each season depends on the puerulus index and effort used in the fishery. The variation in puerulus index plays a more important part in predicting the annual catch than does effort at its current levels experienced by the fishery. In general, catches in zones A and B are rather steady in fluctuation compared with those in zone C. These figures illustrate that density dependence is a lot less in zone C and hence there is a greater variation in catch for this zone. It is clearly important that any estimates attempting to assess the impact of puerulus harvesting on the commercial fishery will need to apply a varying mortality in different years, or areas, in the fishery.

Implications of the results in Section 1 are further discussed in Section 4.

1.2 Estimating mortality between pueruli settlement and recruitment to the fishery

1.2.1 Introduction

To assess the impact of removal of pueruli, we need to have a measure of the absolute abundance of the pueruli that can be linked with the subsequent catches of recruits. It was not possible within the available time and resources to do this for the entire coastline. However, data are available to permit examination of the 29°S –30°S area to test for a method that can estimate the size of puerulus settlement in a given area. These latitudes encompass the area between Dongara and Geraldton, which are near the centre of the Western Rock Lobster Fishery.

For estimating the absolute abundance of puerulus settlement we used archived unpublished CSIRO data on the densities of pueruli and early post-pueruli by depth and by benthos type from studies by Fitzpatrick *et al.* (1989), Jernakoff (1990) and Jernakoff *et al.* (1994) at Seven Mile Beach (Figures 24-26). These data were assumed to be typical of what might have been expected over the region between latitudes 29°S –30°S and the data were extrapolated to this larger area.

We also examined estimates of the density and mortality of juveniles in the Seven Mile Beach area from 1968 to 1984, as calculated by Chittleborough (1970) and Chittleborough and Phillips (1975).

Catch and effort data in this area are available from voluntary fisher logbooks and compulsory catch and effort returns.

1.2.2 Data

Data on the densities of pueruli and post-pueruli up to 25 mm carapace size at Seven Mile Beach from September 1987 to March 1989 were obtained courtesy of CSIRO. These were the basic data on which the Fitzpatrick *et al.* (1990) report to the Fishing Industry Research and Development Council (FIRDC) were based.

GIS coastal mapping data were accessed from the Department of Conservation and Land Management (CALM), Marine Branch, which gave a detailed picture of the distribution of benthos type, by depth, between latitude 29°S –30°S, and these were extrapolated to cover the full degree of latitude. CALM Marine Branch provided the marine habitat type data, which were generated from aerial photograph and satellite image interpretation. The data were transformed into ArcView GIS shape files and an analysis conducted in ArcView. The area of each marine habitat type was calculated using a standard procedure within ArcView, with the resultant values in decimal degree units. These values were converted into square metre units by multiplying the calculated value by a constant (12,347,654,400). The area for "Reef" marine habitat type was determined by adding the area of "Intertidal Reef" and "Subtidal Reef" marine habitat types.

The study by Fitzpatrick *et al*. (1989) and Jernakoff (1990) at Seven Mile Beach and Cliff Head, both within the area of interest, showed that post-pueruli were confined to sheltering in small holes and crevices in hard surfaces at depths of up to 30 m, and that none were found in the seagrass beds or sand. The GIS system was used to identify all the hard surface areas within the 29°S –30°S region (Figure 23). The total area of this type of habitat between the shore and 30 m was estimated to be 382 million m^2.

Figure 23. GIS mapping of the reef at the 29°S –30°S transect of Dongara.

Chittleborough (1970) and Chittleborough and Phillips (1975) estimated the density and mortality of 3, 4 and 5 year olds on the reefs off Seven Mile Beach in the month of January from 1968-1984. The reef densities were estimated by a single census mark recapture experiment, as described in Chittleborough (1970), with some additional data which were obtained from Phillips (1990). The mortality estimates were made based on changes in density between January/February and August/September each year when two single mark-recapture experiments were conducted. The estimates of the 3-year-old animals were made by separating the 3 year olds using modal class composition of the catches. Density estimates of the 4 year old animals were made by applying the natural mortality coefficient of those 3 years and over, to the density of 3 year olds of the earlier year and a similar procedure was used to estimate the density of 5 year old animals.

1.2.3 Methods

An initial examination was made of the above data to determine its suitability and usefulness for the study.

1.2.3.1 Pueruli and post pueruli on reefs

Summarised data on the densities of pueruli and post-pueruli up to 25 mm carapace size at Seven Mile Beach for eight periods between September 1987 to March 1989 were made available by the CSIRO Division of Marine Research. The data were collected during sampling visits to a number of demarcated reefs (each referred to by a reef index number) in the Seven Mile Beach area. The reefs were in depths of up to 20 m and the lobster densities were recorded by divers. Some sampling was also conducted to 30 m. A full description of the study sites and sampling methods are given in Fitzpatrick *et al.* (1989).

The habitat features of a limestone patch reef, typical of shallow coastal areas at Seven Mile Beach are illustrated below (Figure 24). These coastal areas mainly consist of limestone reefs, built from the accumulation of coraline algae, hard corals, shells, molluscs etc.cemented together over time. These reefs are predominantly covered with *Heterozostera/Halophila sp* and *Amphibolis sp* seagrasses. Reef face is defined as that part of the limestone reef surface and that is not part of either a ledge or cave structure. Ledges are found on the surface and at the base of the reefs and generally have a floor of limestone or sand. They are open at the sides and have a sloping roof extending into the reef. Caves are similar to ledges except they are closed at the sides, have restricted light entry and poorer water circulation.

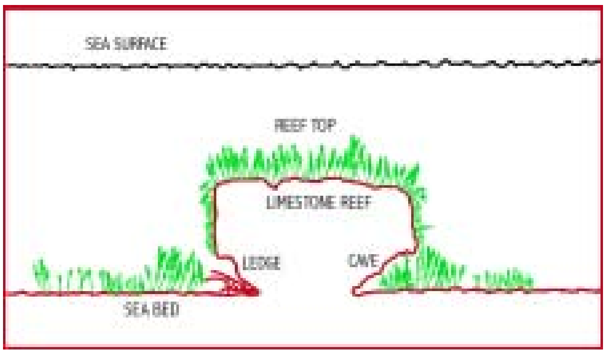

Figure 24. Schematic diagram showing habitat features at shallow coastal areas at Seven Mile Beach. (Adapted from Jernakoff 1990)

The densities for cave, ledge and reef face habitats were recorded separately for each of the reefs in the study site (see Figures 24-26).

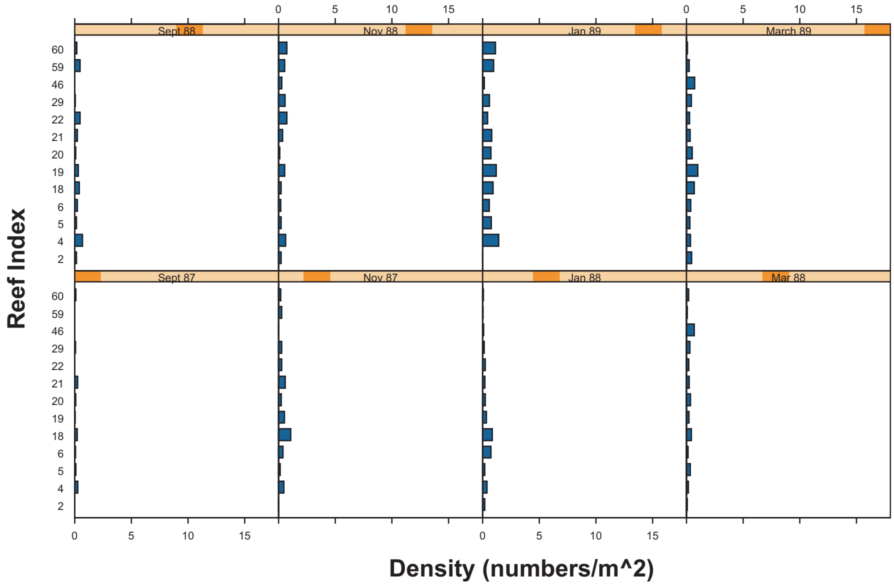

Figure 25. Density of individual *Panulirus cygnus* < 25 mm carapace on the face of the reefs at Seven Mile Beach in 1988/88 and 1988/89.

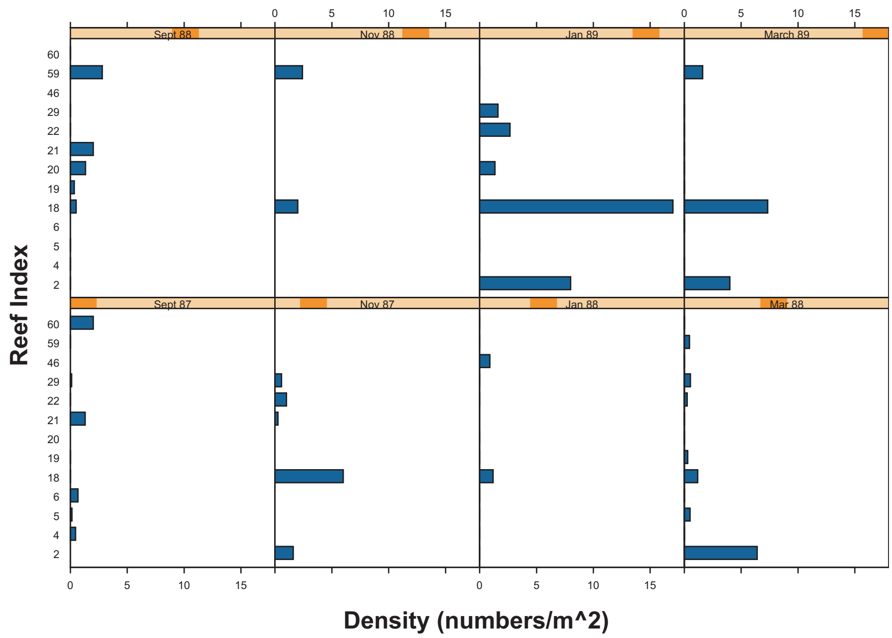

Figure 26. Density of individual *Panulirus cygnus* < 25 mm carapace in caves on the reefs at Seven Mile Beach in 1987/88 and 1988/89.

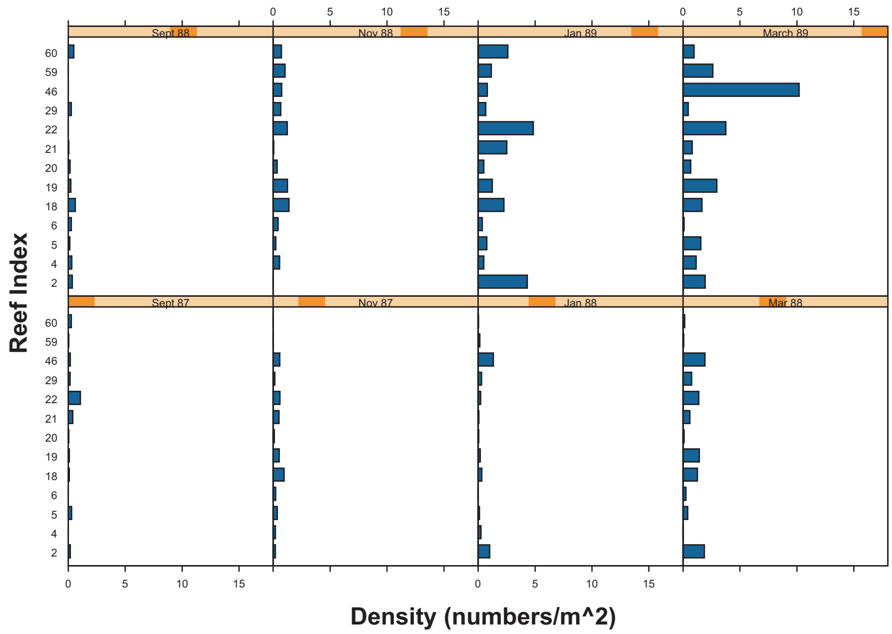

Figure 27. Density of individual *Panulirus cygnus* < 25 mm carapace in ledges on the reefs at Seven Mile Beach in 1987/88 and 1988/89.

Jernakoff (1990) reported that in some months there were differences between the densities of pueruli and post-pueruli <25 mm on the cave, ledge and reef face habitats, but in other months there were not. On the occasions when they were not equal, the densities in the caves and ledges were higher than on the face. Some 60 reefs were examined in the CSIRO study at Seven Mile Beach. The total area of habitat provided by the reefs in Seven Mile beach is comprised of 4% cave, 56% face and 40% ledge habitat (Jernakoff *et al*. 1994). Applying these weights to the mean density / m^2 of each of the habitat types (to produce a number of pueruli and post-pueruli per square metre of reef surface) and summing, the mean densities for the pueruli and post-pueruli <25 mm for the eight periods combined into single monthly densities, are given in Table 6.

Table 6. Estimated reef density of <25 mm pueruli and post-pueruli based on surface area of reef (from Fitzpatrick et al. 1989), with 95% bootstrapped confidence interval.

Month	Year	Mean density (numbers/m^2)	95% Confidence interval 2.50%	97.50%
September	1987	0.1778	0.1041	0.2750
November	1987	0.3506	0.2506	0.4713
January	1988	0.2418	0.1661	0.3391
March	1988	0.4228	0.3145	0.5597
September	1988	0.2483	0.1856	0.3262
November	1988	0.4929	0.3738	0.6356
January	1989	1.3076	0.9298	1.7216
March	1989	0.9198	0.6492	1.2909

The bulk of puerulus settlement takes place over several nights near the time of the new moon, over several months of each year, with a peak in September/October (Phillips 1972). Several studies have been undertaken which show that spiny lobster pueruli and juveniles are very selective as to the size and position of holes in which they choose to settle and shelter (Jernakoff 1990). Based on growth rates of post-pueruli (Phillips *et al.* 1977, Jernakoff *et al.* 1994), the densities of <25 mm juveniles used in this analysis could represent two settlements of pueruli within a season. Because juvenile western lobsters grow rapidly, and because the pueruli settle over an extended period, it is likely that habitat suitable for juvenile animals is used by waves of recruiting animals within a single season.

If, as seems likely, one of the major constraints to juvenile animals is the limit to the amount of habitat available for them to use as shelter, then some assumptions need to be made as to how many animals might utilize the available shelter habitat in a single season. In this study it has been assumed that there are probably the equivalent of two settlements of pueruli that utilise the available reef settlement habitat each year. The mean density figure for each year was determined by summing the mean of the densities for November and March of that year (Table 6). Thus, the mean density for the 1987/88 season was estimated as 0.7734/m^2 and 1.4127/m^2 for the 1988/89 season.

The pueruli density figures are probably conservative as they are based on data on the number of pueruli observed by divers. The limestone reefs in which they were located may contain other caves and ledges in which divers cannot observe the pueruli and young juveniles.

1.2.3.2 Pueruli on collectors related to natural settlement

Fitzpatrick *et al*. (1989) stated: "The densities of pueruli and post-pueruli (<10 mm carapace length) on the reefs at Seven Mile Beach correlate strongly with the densities of similar sized lobsters on artificial collectors at the same site. This indicates that the index of settlement derived from the collectors is an accurate representation of natural settlement, as determined by diver surveys, over a large and spatially variable area at Seven Mile Beach". Jernakoff *et al.* (1994) concluded that this relationship showed: "There was a strong, positive connection between the combined densities of pueruli and early juveniles (<10 mm) on the reefs at Seven Mile Beach, over the eight sampling times ($R = 0.85$, d.f. = 6, $P<0.01$)."

The number of pueruli settling per m^2 at Seven Mile Beach may be calculated as the mean number of pueruli settling on the collectors at Seven Mile Beach, converted to the number per m^2 of surface reef area.

Although puerulus settlement data for reefs and collectors are available for only two years, we assumed that their settlement ratios on the different substrate types were typical of all years. Using the data available (1987/88 and 1988/89 reef densities), the ratio between the collective puerulus index of settlement on collectors at Seven Mile Beach and the collective density of natural settlement for both of these years in the 29°S –30°S area ((puerulus density for 1987/88 + 1988/89)/(puerulus index for 1987/88 + 1988/89)) is 0.015. This figure was used to convert the average puerulus collector index to a predicted density of pueruli per m^2 for years 1968/69 – 1997/98. Based on this information, the predicted likely level of settlement per year from 1968 to 1998 was calculated by multiplying the predicted density per m^2 by the calculated suitable area of reef for puerulus settlement between 29°S –30°S (382.3 million m^2). It should be noted that there was no provided measure of error for the estimate of puerulus per m² between 29°S –30°S. Results of these calculations are presented in Table 7.

Table 7. Estimated number of pueruli settling each season between 1968 to 1998 between latitudes 29°S –30°S at Seven Mile Beach.

Season	Pueruli Index from collectors	Predicted no./m² of reef surface	Predicted no. of Pueruli (in millions)
1968 – 1969	76.50	1.15	439
1969 – 1970	10.00	0.15	57
1970 – 1971	35.00	0.53	201
1971 – 1972	67.17	1.01	385
1972 – 1973	31.00	0.47	178
1973 – 1974	79.83	1.20	458
1974 – 1975	159.50	2.39	915
1975 – 1976	93.67	1.41	537
1976 – 1977	108.50	1.63	622
1977 – 1978	80.83	1.21	464
1978 – 1979	177.17	2.66	1016
1979 – 1980	75.33	1.13	432
1980 – 1981	95.00	1.43	545
1981 – 1982	77.33	1.16	443
1982 – 1983	39.00	0.59	224
1983 – 1984	104.67	1.57	600
1984 – 1985	181.33	2.72	1040
1985 – 1986	121.83	1.83	699
1986 – 1987	58.67	0.88	336
1987 – 1988	59.00	0.89	338
1988 – 1989	84.17	1.26	483
1989 – 1990	206.33	3.09	1183
1990 – 1991	107.17	1.61	615
1991 – 1992	86.67	1.30	497
1992 – 1993	56.33	0.84	323
1993 – 1994	59.67	0.90	342
1994 – 1995	98.67	1.48	566
1995 – 1996	214.00	3.21	1227
1996 – 1997	97.17	1.46	557
1997 – 1998	70.50	1.06	404

1.2.3.3 Juvenile densities and mortalities

The estimates of juvenile densities and mortalities at Seven Mile Beach from Chittleborough and Phillips (1975) and Phillips (1990) are shown in Tables 8 and 9.

Table 8. Estimated densities (number per hectare) of juvenile rock lobsters on the nursery reefs at Seven Mile Beach.

Year	Age group (in years) after hatching		
	3	4	5
1971	2318	1461	1352
1972	2135	978	616
1973	7591	1339	613
1974	5460	3552	621
1975	4316	789	509
1976	5012	2174	397
1977	2828	2598	1127
1978	6145	433	397
1979	4986	1039	73
1980	14803	2281	475
1981	6978	2828	435
1982	4287	1590	644
1983	6154	3668	1360
1984	5193	4285	2553
1985	4085	419	345

Table 9. The estimated mortality coefficient (year $^{-1}$) for juvenile lobsters on the nursery reefs at Seven Mile Beach.

Year	Mortality Coefficient (year $^{-1}$)
1971	0.86
1972	0.47
1973	0.76
1974	1.93
1975	0.69
1976	0.66
1977	1.88
1978	1.78
1979	0.78
1980	1.66
1981	1.48
1982	0.16
1983	0.36
1984	2.52

From the information given in Table 9, the bootstrapped 95% C.I. for M is (0.85, 1.43), with a mean of 1.14 year $^{-1}$. A plot of the estimated probability density for M is presented in Figure 28.

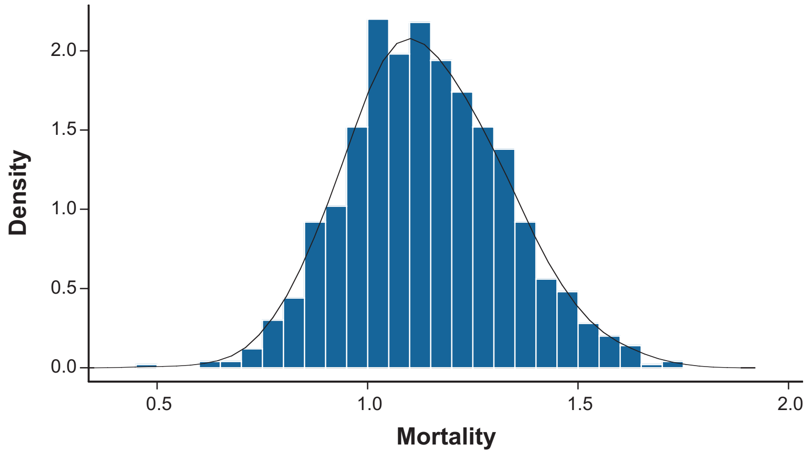

Figure 28. Results from bootstrapping the juvenile mortality coefficients *M* as given in the Chittleborough and Phillips (1975) data. The plot shows the probability density for values of the coefficient.

Considerable time was spent analyzing these density and juvenile data because they represented a possible source of information on the juvenile phase in the nursery reefs. However, there were many problems with these data. For example, the natural mortality rates for legal-sized western rock lobsters have historically been considered to be around 0.226 year $^{-1}$ (Morgan 1977, Walters *et al*. 1993). This would suggest that: -

i) the mortality rates for the juvenile animals (Table 9) have been overestimated;

ii) the estimated mortality of adult lobsters, 0.226 year $^{-1}$ (Morgan, 1977), was under-estimated; or

iii) that the mortality rate for juveniles and adult lobsters differ, with the mortality of lobsters decreasing with increasing age (it may be density dependent mortality).

The data calculated by Chittleborough and Phillips (1975) were based on single mark - recapture estimates. The estimates of the densities and mortalities may not be accurate (Phillips, 1990) since:

i) the sample sizes used in the estimates were small;

ii) it was assumed that there was no emigration or immigration; and

iii) the assumption of equal likelihood of marked and unmarked animals being captured may not be valid.

No further analyses were made of these data in the model described in this part of the study.

1.2.3.4 Proportion of the pueruli settlement to the subsequent catches

In this study, the proportions of puerulus settlement in any particular year which would have contributed to the catches of Grade A and B lobsters 3 and 4 years after settlement have been estimated using 1987/88 and 1988/89 puerulus settlement data and 1990/91, 1991/92 and 1992/93 catch data (Table 12).

Assuming the natural mortality M for legal sized (>76 mm CL) western rock lobsters is 0.226 year $^{-1}$, using the data from Table 7 and Table 12, the abundance of lobsters at time t can be formulated as follows to incorporate proportions of pueruli from settlements 3, 4, and 5 years ago:

If N_t represents the estimated number of lobsters at year t, then

$$N_t = r_{t-3}P_{t-3} + r_{t-4}P_{t-4} + r_{t-5}P_{t-5},$$

where P_{t-3}, P_{t-4}, and P_{t-5} denotes the total number of pueruli settled 3, 4 and 5 years ago respectively, and r_{t-3}, r_{t-4} and r_{t-5} are the proportions of pueruli that contribute to the recruits 3, 4 and 5, years after the settlement respectively. The parameters r_{t-3}, r_{t-4} and r_{t-5} are estimated by a non-linear model similar to (page 7) under the constraint that $r_{t-3} + r_{t-4} + r_{t-5} = 1$.

$$y = \eta(\beta, x) + \varepsilon$$

As calculated in Section 1 of this report, an estimated 40.9% of the puerulus settlement in any given year contributes to the reds catch three years after settlement and 59.0% to the whites catch four years after settlement (Figure 29). There is a small proportion (0.1%) of the puerulus settlement that contributes to the whites catch in the third year, however it is insignificant. These proportions are dependent on the natural mortality rate, which in this case, we have assumed to be $M = 0.226$ per year (based on Morgan 1977).

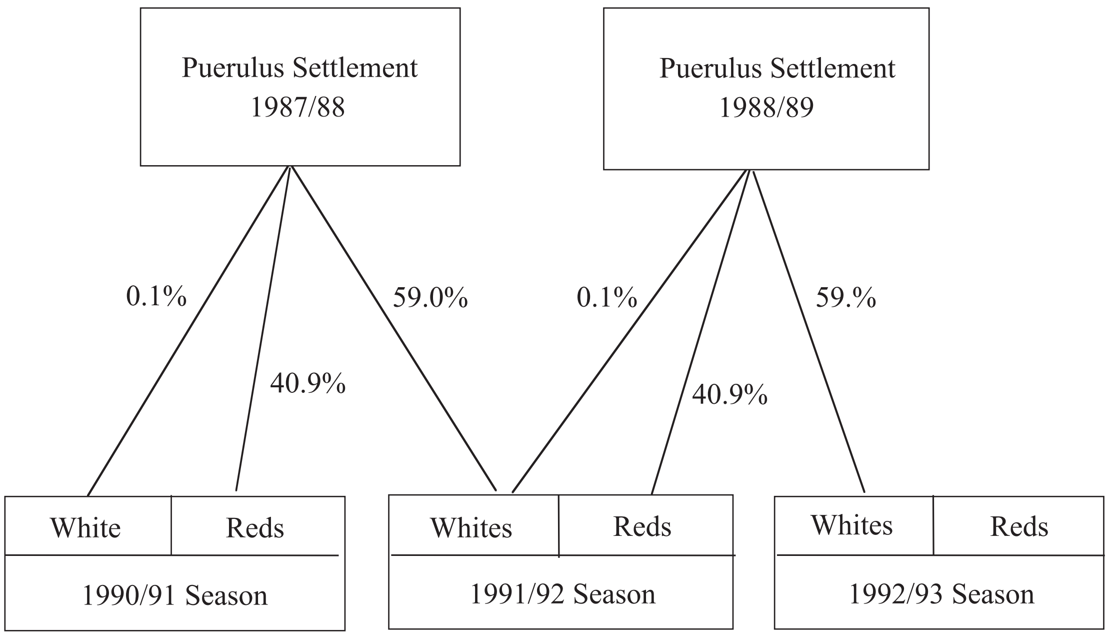

Figure 29. Puerulus settlement of *Panulirus cygnus* and recruitment 3 and 4 years later into the Western Rock Lobster Fishery.

1.2.3.5 Recruits to the fishery

The catches of red and white lobsters in the 29°S –30°S area in the 1990/91, 1991/92 and 1992/93 seasons have been estimated using fisheries compulsory catch and effort returns, which are submitted by commercial fishers to the Department of Fisheries in WA on a monthly basis.

The total number of animals estimated to have recruited into the fishery in the 1991/92 season and the 1990/91 and 1992/93 red and white seasons respectively, was used to estimate mortality rates between settlement and recruitment over these periods. A schematic diagram (Figure 29) shows the proportions of the catch that have been estimated to contribute to the reds and whites part of the catch in the various seasons under consideration.

The white and red lobsters are classified as Grade A (carapace length between 76 – 79 mm), or Grade B (carapace length between 80 – 88 mm).

To determine the weight of the Grade A and B lobsters landed each season as a proportion of the total catch, two data sets have been considered; namely commercial monitoring length frequency data and factory production data. Commercial monitoring data contain length frequency samples of catches measured in different depths each month throughout the fishing season. Lobsters are recorded according to the following characteristics: sex, red/white colouration, spawner, tarspot, setose, location/sublocation, depth and carapace length. Factory production data have been recorded as the weight of lobsters packed by factory location, by grade, for each fishing season. Although factory production data do provide a more complete record of the number of catches for each size of lobsters, they do not relate to catches made to a specific region (i.e. in this case the Dongara region). Commercial monitoring length frequency data for the Dongara area have been used to compensate for the lack of area-specific information in the factory production statistics.

The proportion of 76-88 mm lobsters compared to larger sizes in the commercial monitoring data has been considered to provide an estimate of the contribution that Grade A and Grade B lobsters make to the total catch throughout the fishing season.

Assuming the proportion of Grade A and Grade B catches are constant throughout the season, an estimate of the number of pueruli that settled 3 and 4 years earlier and have survived to recruit as Grade A and B animals has been calculated as follows:

- In the 1992/93 season new regulations were introduced, including a 10% reduction in pot numbers (Rock Lobster Industry Advisory Committee 1993). Due to the commencement of these regulations requiring a significant period to be fully implemented across the whole fishery however, the effects of these new regulations were not fully evident until 1993/94. We have assumed that these effects are negligible in the 1992/93 season and hence, the catch data has not been adjusted.

- The weight of lobsters landed for the area between latitudes 29°S –30°S has been calculated from compulsory commercial catch and effort data. The proportion of the Grade A and B lobsters (the size class of animal considered to be newly recruited to the fishery) comprising the total catch, has been estimated in each season (see Table 10). This proportion multiplied by the total catch gives the number of grade A and B lobsters caught. An exploitation rate of 0.62 (N. Hall, pers. comm.) has been used to raise these seasonal landings of Grade A and B lobsters to an estimate of the total weight of animals present in these grades in the area being considered for each season.

- The total weights were then converted to numbers of lobsters. A male lobster of A or B grade weighs between 399 and 607 grams and a female between 420 and 673 grams (Fisheries WA, unpub. data). We have assumed the mean weight of an animal in these grades to be 500 grams and have used that figure to calculate the number of A and B grade lobsters landed between 29°S –30°S in Table 13.

It has been assumed in this section that the contribution made by recreational rock lobster fishers to the total catch and effort in the area is insignificant. It has been estimated that approximately 2% of recreational rock lobster fishing effort in the 1998/99 season occurred in the area corresponding to that between latitudes 29°S –30°S (Melville-Smith and Anderton 2000). If recreational catch and effort were directly proportional, then the rock lobster catch made by recreational fishers in this area in 1998/99 would have been an estimated 13 tonne. The recreational rock lobster catch in the 1998/99 season was the highest that had been recorded by that sector up to that time (Melville Smith and Anderton 2000). It can therefore be assumed that the recreational rock lobster catch made between 29°S –30°S in previous seasons was less than 13 t and compared to the commercial catch, of insignificant proportions.

1.2.4 Results

1.2.4.1 Pueruli and post-pueruli

The densities of individuals in the <25 mm range during 1987-89 provide an estimate of total numbers of settling pueruli.

Table 10. Proportion, by number, of lobsters categorised by grades - sizes A and B (76 – 88 mm CL) compared to other grade (>88 mm CL) - from the commercial monitoring data for 1990/91, 1991/92 and 1992/93 seasons at Dongara.

	1990/91	1991/92	1992/93
Small lobsters (Grade A + Grade B)	0.93	0.91	0.91
Large lobsters (Grade C and above)	0.07	0.09	0.09

Table 11. Estimated number of individual *Panulirus cygnus* pueruli and post -pueruli within the 29°S –30°S area.

Season	Mean density of puerulus (Number per m^2)	Mean (millions)	Lower boundary (95% confidence interval)	Upper boundary (95% confidence interval)
1987/88	0.7734	338	216	394
1988/89	1.4127	483	391	736

Table 11 was derived using non parametric bootstrapping to calculate the mean and the associated (empirical) 95% CI for puerulus densities of the sampled reef areas given in Table 6. As noted earlier under methods, the densities of <25 mm pueruli and post-pueruli compiled in Table 6 could represent two settlements of pueruli within a season. The estimated seasonal densities of pueruli have been multiplied by the estimated surface reef area in the 29°S -30°S transect (382 million m^2) to provide an estimate of the number of one year old animals in the area under consideration (Table 11).

1.2.4.2 Juveniles in nursery reefs

Because of the questions about the accuracy of the juvenile data it was concluded that the data on the juvenile densities and mortalities from Chittelborough (1970) and Chittleborourgh and Phillips (1975) were not useful for these analyses. However, they were useful in suggesting that the mortality of juveniles from age 2 to 5 on the nursery reefs might be higher than for legal-sized lobsters i.e. higher than the $M = 0.226$ year $^{-1}$ calculated by Morgan (1977) for legal sized lobsters.

1.2.4.3 Recruits to the fishery

Tables 10 and 12 show the proportions of legal sized animals categorised as small animals (Grade A and Grade B) and large animals (Grade C and above) for the 1990/91, 1991/92, and 1992/93 seasons. Note that the results obtained from the commercial monitoring data are for the Dongara region only and the results obtained from factory production data are for one factory that collects its processed catch from the entire Northern region of the fishing grounds (i.e. from Jurien to Shark Bay, including the Abrolhos Islands). These proportions from the two data sources are very close (Table 10 and 12) and hence provide justification for using the commercial monitoring data for the Dongara region.

Table 12. Proportion, by number, of lobsters categorised by grades - sizes A and B (76 - 88 mm CL) compared to other grade (>88 mm CL) - from factory production data for the Northern region for 1990/91, 1991/92 and 1992/93 seasons.

	1990/91	1991/92	1992/93
Small lobsters (Grade A + Grade B)	0.96	0.97	0.98
Large lobsters (Grade C and above)	0.05	0.03	0.02

The proportion of catches that are “small” (Grade A and B) lobsters for the 1990/91, 1991/92 and 1992/93 seasons from the commercial monitoring data are 92.7%, 91.1% and 91.2% respectively (Table 10).

Table 13. Number of lobsters of Grade A and Grade B for seasons 1990/1991, 1991/92 and 1992/93.

	whites	reds	total
1990/91	3,779,242	2,752,221	6,531,463
1991/92	3,623,867	3,473,997	7,097,864
1992/93	3,653,131	2,655,541	6,308,672

Based on the above information in Table 13, the size of the settlement that survived through to recruit to the commercial fishery from particular settlement seasons is estimated to be 6,376,088 from the 1987/88 settlement (red catch 1990/91 + white catch 1991/92) and 7,127,128 from the 1988/89 settlement (red catch 1991/92 + white catch 1992/93).

1.2.4.4 Mortality Estimates

The mortality rate between settlement and recruitment to the fishery can be estimated by dividing the eventual number of recruits from a particular settlement season by the estimated puerulus settlement of that season. Based on the forgoing calculations, mortality over this period of the life history has been estimated as 98.11%, and 98.52% for the 1987/88 and 1988/89 puerulus seasons, respectively.

Although we can estimate the total mortality from puerulus settlement to recruitment into the fisheries, we do not know the distribution of the mortality over the three year period. In the absence of other information we have made the assumption in this section that natural mortality remains constant throughout the animal's life from the second year after settlement. Morgan (1977) estimated natural mortality of legal sized *P. cygnus* to be 20% per annum, at an instantaneous rate of M=0.226 year $^{-1}$. This mortality rate was applied retrospectively to those animals that were estimated to have survived from the 1987/88 and 1988/89 settlement between 29°S–30°S (Table 13). The results predict that the mortality in the first year after the settlement (age = 2) was 97.1% for the 1987/88 settlement and 98.7% for the 1988/89 settlement (Figures 30–31)

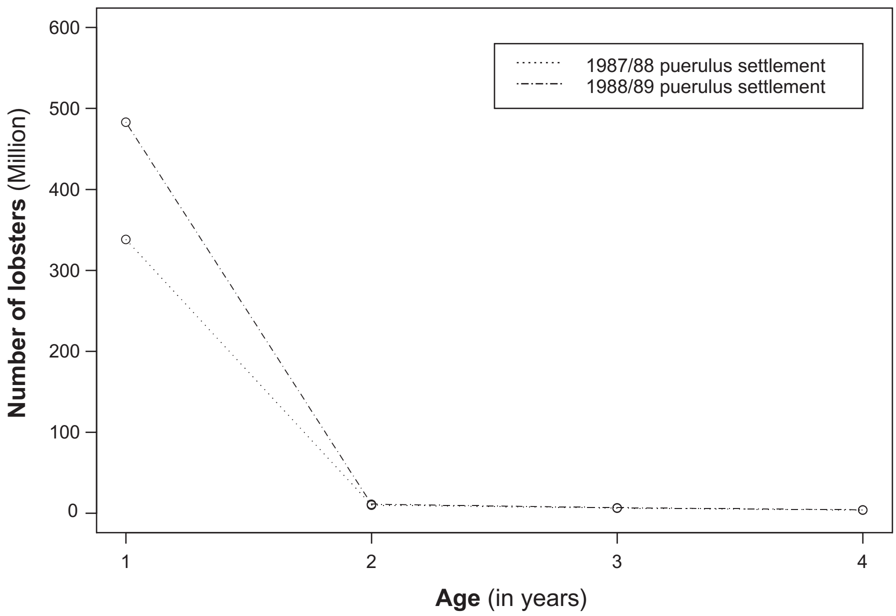

Figure 30. Depletion of *Panulirus cygnus* pueruli and juveniles from settlement (age 1 years) to age 4 years for the 1987/88 and 1988/89 settlement seasons. Estimate made using a constant mortality rate between years 2 to 4.

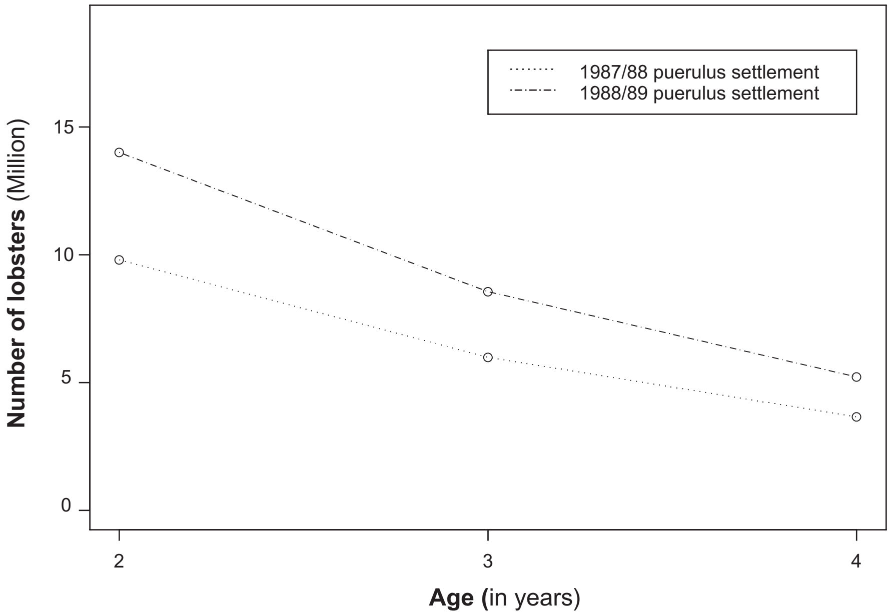

Figure 31. Depletion of *Panulirus cygnus* pueruli and juveniles from age 2 years to age 4 years, for the 1987/88 and 1988/89 settlement seasons. Estimate made using a constant mortality rate between years 2 to 4.

Between 0.9 and 6.4% were estimated to survive between settlement and recruitment to the fishery at about 4.5 years of age.

1.2.5 Discussion

The mortalities of 97.1% in the 1987/88 season and 97.97% in the 1988/89 season for *P.cygnus* are very close to those estimated by Marx (1986) and Butler (1994) for *Panulirus argus*. They estimated that for *P. argus* only 3% of settling pueruli survive the first year after settlement, but from the second year after settlement onwards the mortality rate reduces significantly through to recruitment into the fishery.

It was suggested (P. Breen, NIWA, pers.comm.) that natural mortality rates for the red rock lobster, *Jasus edwardsii* in New Zealand, might be in the order of 75% in the first year after settlement, 25% to year three and 10% thereafter. *P. cygnus*, being more closely related to *P. argus* and also being a warm water lobster, would be more likely to share similar mortality rates to *P. argus* than *J. edwardsii*.

One of the least likely assumptions that has been made in the model discussed in this section is that there is a constant mortality rate from the second year after settlement. However, it is inappropriate to use M=0.226 year $^{-1}$ when studying lobsters in the early juvenile stages when they are presumably more vulnerable to predators. It is likely that natural mortality would gradually decline before reaching the levels calculated by Morgan (1977) for legal-sized animals. In Section 3 a more likely series of estimates of juvenile mortality during the period prior to entry to the fishery, are examined.

It should be pointed out that even:-

- if the density estimates had been incorrect by an order of magnitude (due for example to the amount of reef area between 29°S - 30°S being incorrectly estimated, the density of pueruli being less uniform than considered here, or there being more/less than the equivalent of two full monthly settlements of pueruli each season), then the mortality in the first year after settlement estimated in this document would differ by only a few percent from the result obtained; and

- the critical figure is therefore the assumption of M and to possibly a lesser extent, the calculation of legal sized recruits to the commercial fishery.

1.3 Pueruli density mortality model development

1.3.1 Introduction

A simple descriptive model was developed to represent the flow of lobsters from pueruli settlement on coastal reefs to their subsequent recruitment to the fishery. A model was also developed for improved puerulus index-recruitment relationships. These models were used to examine the impact of possible puerulus harvests on the catches obtained by fishers in order to assess implications for removals on the breeding stock. If puerulus removals are permitted, a possible method of achieving biological neutrality by reductions in fishing effort is examined.

1.3.2 Analyses

1.3.2.1 New approach to estimating mortality parameters

A primary factor that determines the number of pueruli/lobsters of a given brood surviving to t years after settlement is the natural mortality M. A classic assumption is that the natural mortality for fish populations of all ages is constant and independent of population density (reviewed in Beverton & Holt 1957, p 28). However, the mathematical population model based on this assumption does not prove to be useful (reviewed in Beverton & Holt 1957, p 46), particularly when considering post-larval stages like the puerulus.

A more appropriate assumption made in this model, is that the mortality at time is dependent on the population size at time t, i.e. the basis behind the Beverton-Holt stock-recruitment curve (Beverton & Holt 1957). A true relationship between mortality rate and the density of a particular cohort can represent numerous biological phenomena, including competition for food or space (Hilborn & Walters 1992). In the case of lobsters, competition may be related to limited reef with shelters of dimensions suitable for settlement by pueruli and early stage juveniles. This model, as will be seen below, has attempted to take these considerations into account.

The mortality value of 0.226 year^{-1} reported by Morgan (1977) is quoted extensively in the literature. However, it is an estimated mortality for adult lobsters at the Abrolhos Islands. Thus, it is inappropriate to use this figure when studying lobsters in the early juvenile stages when they are very vulnerable, or for very large animals that are moulting infrequently, and because of their size, are less vulnerable to predation.

This section attempts to directly estimate the density and fishing mortality of pueruli based on the density-dependent mortality model, using annual catch, effort and puerulus indices from 29°S to 30°S for the years 1968/69-1997/98. The model assumes that the mortality at time t is dependent on the population size at time t. One of the biological supports for this assumption is the consequence of competition for shelter at young ages (Beverton & Holt 1957). In addition, the density-dependent mortality is evident in the puerulus-catch relationships (Caputi *et al*, 1996, and Section 1 of this study).

Fishing mortality also plays an important role in determining the population size of the animal depending on the age of the animal (or the phase of the life span it reaches). Prior to the animals becoming available to the fishery, fishing mortality has been assumed to be insignificant. This assumption has been made because discard mortality rates are believed to have been minimised as a result of research (Brown and Caputi 1986) and programs aimed at improving best fishing practice. However, once the lobsters reach 4 or 5 years of age (i.e. 3 years, or 4 years, after puerulus settlement), they become accessible to fishing and the mortality coefficient then needs to include both natural and fishing mortality. It is also necessary to estimate a fishing mortality that is dependent on the lobsters' age of recruitment to the fishery, since as seen in Section 2 (Figure 26), a significant proportion of each cohort first recruit to the fishery 3 and 4 years after settlement i.e. 40.99% of a particular cohort first recruit to the fishery 3 years after settlement and the other 59.01% another year later (other ages of first year of recruitment to the fishery have been assumed negligible).

In the previous methods the fishing mortality has been assumed to be the same for lobsters of all ages in the fishery. Our new approach has been to divide fishing mortality into two components: F_i, the fishing mortality of lobsters initially recruited to the fishery 3 years after settlement, and F_2, the fishing mortality of lobsters initially recruited to the fishery 4 years after settlement. These mortalities are calculated by $F_i = e_{F_i} E_{ff}$, where e_{F_i} is the age specific vulnerability to fishing mortality, and E_{ff} is the fishing effort (in terms of millions of pot lifts). Using this equation for fishing effort, we have assumed that there was no exaggerated fishing effort i.e. catch rate is independent of the level of effort. Methods in Section 1 and 2 have failed to incorporate pot lift data into their calculation of mortality parameters.

This new approach can estimate both fishing and asymptotic mortality simultaneously. Traditionally, the estimation of fishing mortality is based on the assumption of a fixed asymptotic mortality rate. However, since fishing and asymptotic mortality are expected to be correlated (see the results in this section), the traditional method of estimating the fishing mortality may be biased.

Before entering the fishery (i.e. rock lobsters of ages = 1, 2, 3 years), the instantaneous rate of mortality dependent on population density for lobsters t years after settlement can be expressed as an alternative form of the Beverton and Holt stock-recruitment relationship:

$$\frac{dN_t}{dt} = -(M_d + q_d N_t)N_t, \qquad q_d \geq 0\,, \qquad \textbf{(3.1)}$$

where M_d is the asymptotic mortality when $N_{t,\,s}$ approaches to zero, and q_d is the density-dependent mortality. Note that in this instance we are modelling the number of lobsters remaining in a particular cohort at time t as opposed to the catch and puerulus index relationship explored in Section 1.

We have not assumed an asymptotic mortality value of 0.226 year^{-1} as calculated by Morgan (1977); but instead estimate it along with the other required parameters.

By integrating both sides of the equation, we derive an expression for the population (number of lobsters/pueruli) t years after settlement from an initial cohort size N_0, given there is no fishing (Equation (2)).

$$N_t(N_0) = \frac{N_0 M_d\, e^{-M_d t}}{M_d + N_0\, q_d (1 - e^{-M_d t})} \qquad \textbf{(3.2)}$$

Three or four years after settlement (i.e. when lobsters are aged 4 or 5 years) lobsters recruit to the fishery. We will assume, based on results obtained in Section 1 (of this document), that the average time for recruitment into the fishery from settlement, is 3.5 and 4.5 years. During the fishing season, these lobsters recruit to the fishery with additional mortality (fishing mortality) F_1 and F_2, respectively. An important assumption required at this stage is that fishing and natural mortality occur simultaneously and independently. Equation (3) describes the instantaneous rate of mortality for lobsters during the fishing season 3 and 4 years after settlement.

$$\frac{dN_t}{dt} = -(Z_i + q_d N_t) N_t \qquad q_d \geq 0, \qquad \textbf{(3.3)}$$

where:

- $Z_i = F_i + M_d$ is the total mortality coefficient of lobsters recruiting to the fishery 2.5+*i* years after settlement;
- F_i is the fishing mortality of legal sized lobsters 2.5+*i* years after settlement; and
- $i = \lfloor t - 3.5 \rfloor + 1$.

It should be noted that (3.3) holds only when t is a time of fishing, otherwise, (3.1) is the correct formulation of N_t i.e. $F_1 = F_2 = 0$.

As previously, we integrate (3.3) to obtain the population t years after settlement (Equation (3.4)).

$$N_t^*(\overline{N_i}, Z_i) = \frac{\overline{N_i} Z_i\, e^{-Z_i (t-2.5-i)}}{Z_i + \overline{N_i}\, q_d (1 - e^{-Z_i (t-2.5-i)})} \qquad \textbf{(3.4)}$$

where $3.5 \leq t \leq 4.125$, $4.5 \leq t \leq 5.125$ and $\overline{N_i}$ is the number of lobsters remaining of the cohort at the beginning of the *i*'th fishing season.

It should be noted that the length of the fishing season is 0.625 years (7.5 months), the only period during which fishing mortality is applicable to the mortality of lobsters.

Unless otherwise stated, reference to catch will be in terms of units (number of lobsters caught). When catch has been transformed to weight, it has been assumed throughout, that a lobster weighs 0.5 kg.

The instantaneous rate of catches in year* s *with respect to lobsters* j *years after settlement is:

$$\frac{dC_t}{dt} = F_i N_t,\; i = 1,2 \qquad \textbf{(3.5)}$$

It is assumed for what proceeds, that the catch from a particular cohort is split into 2 classes: one class is subject to fishing mortality in the fishing season 3 years after settlement whilst the other class, in the fishing season 4 years after settlement. That is, it is assumed that what remains of $r_1 N_0$ of the cohort in the fishing season 3 years after settlement are the only available lobsters to the fishery, of that cohort. What remains of those r lobsters at the end of that fishing season will not enter the fishery again. Similarly, what remains of $(1 - r_1)N_0$ of the cohort at the beginning of the fishing season 4 years after settlement, are the only available lobsters to the fishery, of that cohort.

It follows that the expression for the number caught at age j to $j + t_L$ from an initial cohort population N_0, with fishing time t_L is:

$$C(j,t_L,F_i) = r_i F_i \left\{ \frac{-(F_i + M_d)t_L}{q_d} + \left((F_i + M_d)N_j + \frac{(F_i + M_d)^2}{q_d} \right) \times \left(\frac{ln\left(N_j q_d + F_i + M_d - N_j q_d e^{-(F_i + M_d)t_L}\right) - ln(F_i + M_d)}{(F_i + M_d)(N_j q_d + F_i + M_d)} + \frac{t_L}{N_j q_d + F_i + M_d} \right) \right\}$$

(3.6)

where:

- $t_L = \frac{7.5}{12}$ is the length of the fishing period being considered;
- j is the age (in terms of years after settlement) of the lobster being considered, which we will assume to be either 3.5 or 4.5 when making forecasts and 3 and 4 when estimating parameters;
- r_i is the proportion of the original cohort that contribute to the age j catch where $r_1 = 0.4099$ and:

$$r_2 = \frac{(1 - r_1)N_{4.125}(N_0)}{r_1 N^*_{4.125}(N_{3.5}(N_0), Z_1 = M_d + F_1) + (1 - r_1)N_{4.125}(N_0)}$$

  i.e. r_2 is the proportion of the initial cohort to remain at the end of the first fishing season to have affected it, that actually belongs to the second class; and
- $i = \lfloor t - 3.5 \rfloor + 1$;

Following the previously made assumptions about the probability of a lobster recruiting to the fishery at a particular age, the total future catch (Q) from a particular initial cohort with size is:

$$Q(F_1, F_2) = \begin{matrix} C(j = 3.5, t_L = 7.5/12, F_1) + \\ C(j = 4.5, t_L = 7.5/12, F_2) \end{matrix} \qquad \textbf{(3.7)}$$

where $t_L = \frac{7.5}{12}$ is the length of the western rock lobster fishing season in years. We used this formulation to make forecasts concerning future catches. In this way any proceeding catch reduction charts refer to the reduction of total catch from a particular cohort over the assumed two age groups.

It should be noted that Equation (3.7) can be used to describe the future catch in a particular year if we are given the two initial cohort sizes that give rise to the 4 and 5 year olds of that particular year's catch. In this way, Equation (3.7) has been used to estimate the mortality parameters.

Using information from Table 7, along with collected catch and effort data between the associated latitudes of 29°S –30°S at Seven Mile Beach, we have used non-linear regression to determine the parameters e_{F_1}, e_{F_2}, q_d and M_d. We have then calculated F_1 and F_2 by the relationship $F_i = e_{F_i} E_{ff}$, $i = 1,2$. We have made the following assumptions about, and adjustments to the catch and effort data from 1968/69-1997/98:

- that the contribution made by recreational rock lobster fishers to the total catch and effort in the area is insignificant. It has been estimated that approximately 2% of recreational rock lobster fishing effort in the 1998/99 season occurred in the area corresponding to that between latitudes 29°S – 30°S (Melville-Smith and Anderton 2000). If recreational catch and effort were directly proportional, then the rock lobster catch made by recreational fishers in this area in 1998/99 would have been an estimated 13 tonnes. The recreational rock lobster catch in the 1998/99 season was the highest on record monitored by that sector (Melville Smith and Anderton 2000). It can therefore be assumed that the recreational rock lobster catch made between 29°S –30°S in previous seasons was less than 13 tonnes and compared to the commercial catch, of insignificant proportions. The catch by this sector has therefore been excluded from the analyses in this section;
- the introduced policy changes to the lobster fishery in 1993/94 have resulted in a 17% reduction in total catch in 1993/94 and a 4.6% reduction in subsequent years (N. Caputi, *pers. comm.*). We adjusted the total catch of 1993/94 by dividing it by 0.83 and the catches of subsequent years by 0.954; and
- technological factors causing more effective fishing effort over the years have not been considered for the 29°S – 30°S region. We chose not to include these factors because the unadjusted catch rate (in terms of technological factors) is more independent of the level of effort (p=0.7106) than the adjusted catch rate (p=0.3789) calculated using a 1.2% increase in pot effectiveness each season from 1971/72 (N.Caputi, *pers. comm*.). Assuming that effort and catch are independent validates the use of the relationship:

$$F_i = e_{F_i} E_{ff}, \; i = 1,2 \qquad \textbf{(3.8)}$$

1.3.2.2 Estimation of total mortality

Based on these assumptions in Analyses, density dependent mortality $M(N_t)$ can be estimated by:

$$M(N_t) = M_d + q_d N_t(N_0)$$

if t ≤ 3.5;

$$M(N_t) = r_1\left(M_d + F_1 + q_d\, N_t^*\left(N_{3.5}(N_0), Z_1 = M_d + F_1\right)\right) + (1 - r_1)\left(M_d + q_d N_t(N_0)\right)$$

if 3.5< t ≤4.125

$$M(N_t) = M_d + q_d\, N_{t-4.125}(\eta_1)$$

where

$$\eta_1 = r_1 N_{4.125}^*\left(N_{3.5}(N_0), Z_1 = M_d + F_1\right) + (1 - r_1) N_{4.125}(N_0),$$

if 4.125< t ≤4.5;

$$M(N_t) = (1 - r_2)\left(M_d + q_d N_{t-4.125}(\eta_1)\right) + r_2\left(M_d + F_1 + q_d\, N_t^*\left(N_{0.375}(\eta_1), Z_2 = M_d + F_2\right)\right)$$

if 4. 5< t ≤5.125; and

$$M(N_t) = M_d + q_d N_{t-5.125}(\eta_2)$$

where

$$\eta_2 = (1 - r_2) N_1(\eta_1) + r_2 N_{5.125}^*\left(N_{0.375}(\eta_1), Z_2 = M_d + F_2\right)$$

if t > 5.125

(3.9)

where N_t is the cohort size in millions, at time t, and N_t and N^*_t refer to the use of equations (3.2) and (3.4), respectively.

1.3.2.3 Biological neutrality

The proportion of total catch expected from a particular cohort (with no puerulus harvesting and no fishing effort reduction) P_Q, resulting from both fishing effort reduction (1- P_{Ef}) and puerulus harvesting (1- P_p) is

$$P_Q = \frac{Q(P_{Ef}\, F_1, P_{Ef}\, F_2)\Big|_{let\ N_0 = P_p N_0}}{Q(F_1, F_2)} \qquad \textbf{(3.10)}$$

Using equation (3.10) we can determine the reduction in catch for particular levels of reduction in effort and harvesting of pueruli, so as to gauge the possible reduction in allowable fishing effort if we are to harvest a particular percentage of pueruli, but still achieve biological neutrality.

1.3.3 Results

Table 14. Correlation matrix for estimated parameters of Equation (3.7) using the Seven Mile Beach data set.

	M_d	q_d	e_{F1}
q_d	-0.049		
e_{F1}	0.804	0.390	
e_{F2}	0.837	0.328	0.668

Performing a non-linear regression of Equation (3.6) with the commercial catch and effort data, for the associated latitudes of 29°S - 30°S at Seven Mile Beach, we get a model with SSE = 2.2242 and parameter estimates $M_d = 0.6696$ (s.e.= 0.1142), $q_d = 0.0062$ (s.e.= 0.0012), $E_{FF} = 2.2819$, $e_{F1} = 0.4147$ (s.e.= 0.2307) $\Rightarrow$ $F_1 = e_{F1}\,E_{FF} = 0.9463$, and $e_{F2} = 0.9216$ (s.e.= 0.6405) $\Rightarrow$ $F2 = e_{F2}\,E_{FF} = 2.1031$.

The correlations for these parameter estimates, which are required to construct confidence intervals for predicted catch, are presented in Table 14. A graphic illustrating the effectiveness of this model can be seen in a prediction of catch in the 29°S to 30°S transect of Dongara as presented as Figure 32.

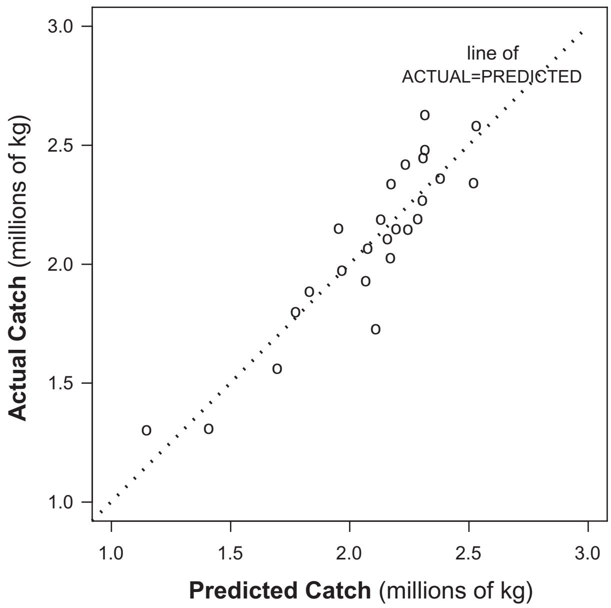

Figure 32. Actual catch of *Panulirus cygnus* versus the predicted catch of model (3.7) for the 29°S to 30°S transect of Dongara.

Equations **(3.2)** and **(3.4)** provide continuous relationships between age and population size for which fishing effort is both excluded and included. These are represented in Figures 33-35, respectively. The estimated total mortality (Equation 3.8) for which fishing effort is assessed is shown graphically in Figures 36–37. They illustrate the change in the population size with density dependent mortality.

Table 15. Estimated population of *Panulirus cygnus* (N_t) at t (age in years) and the estimated total mortality $M(N)$ based on the data from the 29°S to 30°S region, and assuming no fishing mortality. The data in brackets represent the percentage of lobsters remaining from the initial cohort size.

	1987/88			1988/89		
t (age in years)	N_t (million)		$M(N_t)$	N_t (million)		$M(N_t)$
1	338	(100%)	2.77	483	(100%)	3.67
2	68.37	(20.2%)	1.09	77.58	(16.1%)	1.15
3	26.72	(7.7%)	0.84	29.39	(6.1%)	0.85
4	12.20	(3.6%)	0.74	13.28	(2.8%)	0.75
5	5.92	(1.8%)	0.71	6.41	(1.3%)	0.71
6	1.74	(0.5%)	0.68	1.88	(0.4%)	0.68

For simplicity, fishing mortality was not considered in Figures 33-34. There is a steep decrease in the population between year 1 and year 2. Also, the rate of decrease between the first and second year increases as the level of puerulus settlement increases. The rate of change slows down as time progresses. Table 15 presents the percentage of lobsters remaining, of the initial settlement, for Figures 33-34, as well as the number remaining at one year intervals.

Caputi *et al.* (1995a, p.253) show that for example in Dongara, a 50% drop in puerulus settlement causes a 15% drop in catch. This relationship is evident in Equation (3.7) as illustrated in Figures 38-39. The model presented in this section is different to those models presented in Section 1 in that this model deals explicitly with effort data in an attempt to explain catch levels and hence, there is a closer relationship between catch and effort.

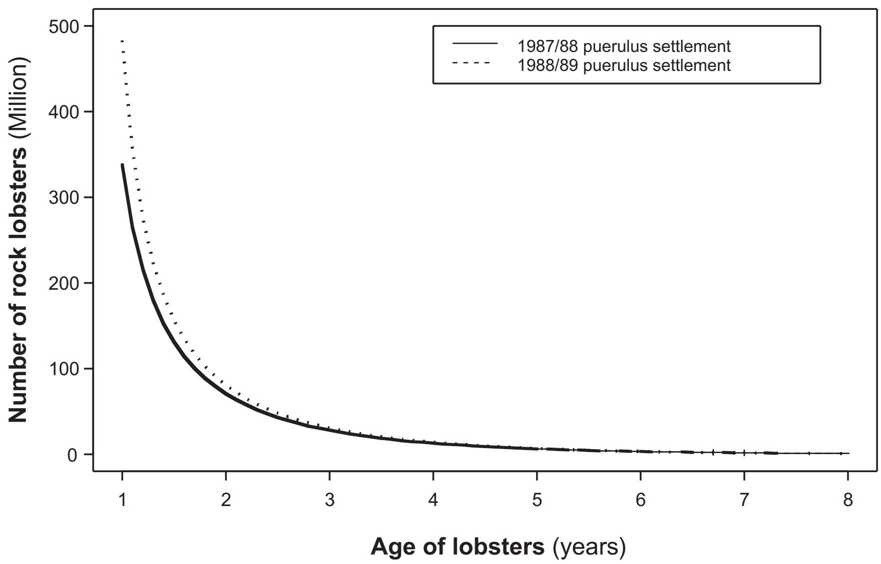

Figure 33. Change in the population size of *Panulirus cygnus* with no fishing effort versus age.

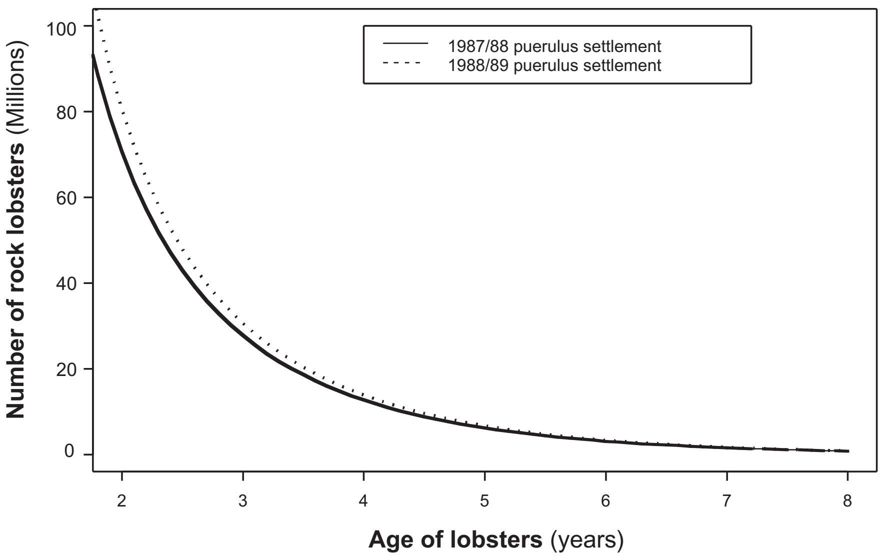

Figure 34. Modelled change in the population size of *Panulirus cygnus* in the region between 29°S and 30°S . The figure shows the simulation result from age 2 to 8 and excludes fishing effort.

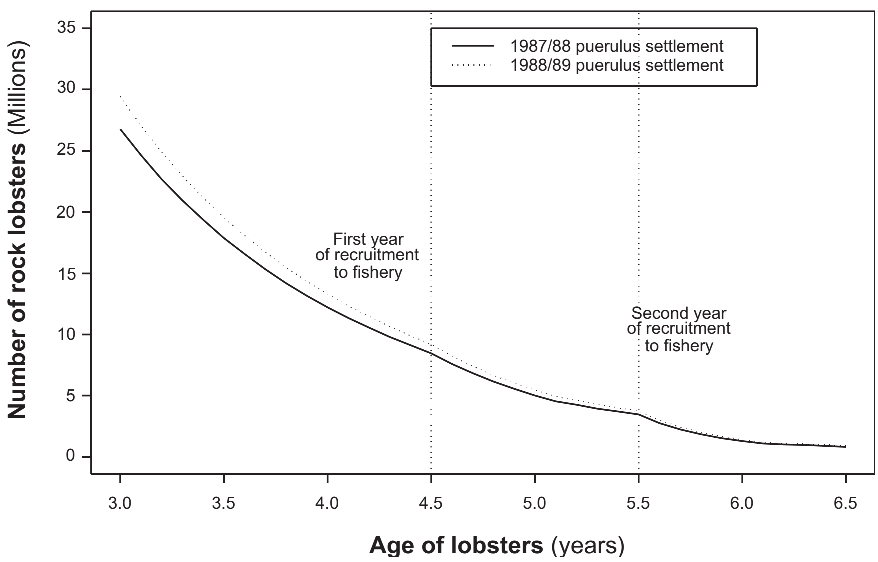

Figure 35. Modelled change in the population size of *Panulirus cygnus* in the region between 29°S and 30°S. The figure shows the simulation result from ages 3 to 6.5 and includes fishing effort.

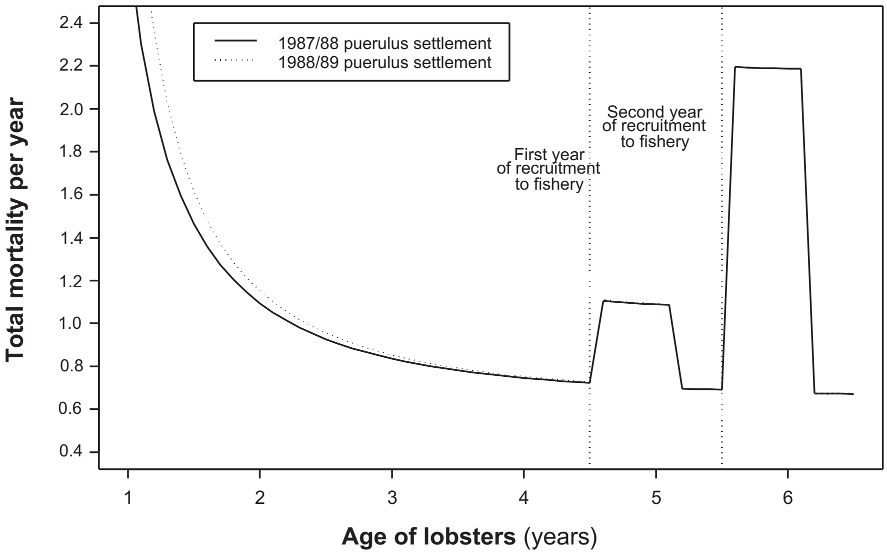

Figure 36. The change in total mortality change for the population of *Panulirus cygnus* against age with fishing effort, illustrated from age 1 year.

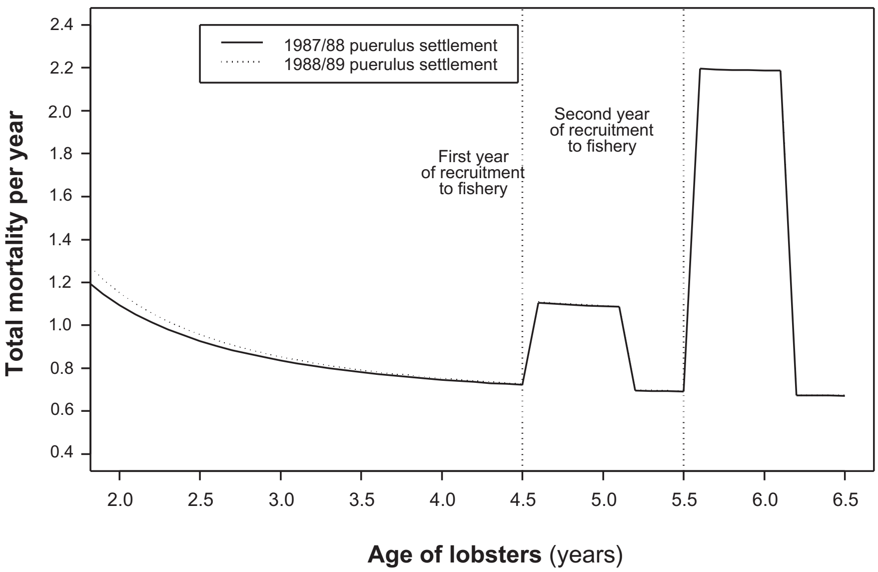

Figure 37. The change in total mortality for the population of *Panulirus cygnus* against age, illustrated from age 2 with fishing effort.

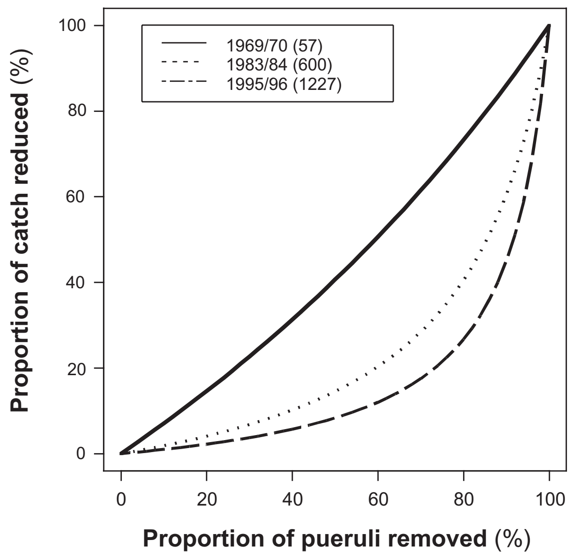

Figure 38. Effect of proportion of pueruli of *Panulirus cygnus* removed against proportion of recruitment to the fishery for three levels of puerulus settlement: the highest, lowest, and a medium level of puerulus settlement recorded in the 29°S to 30°S region.

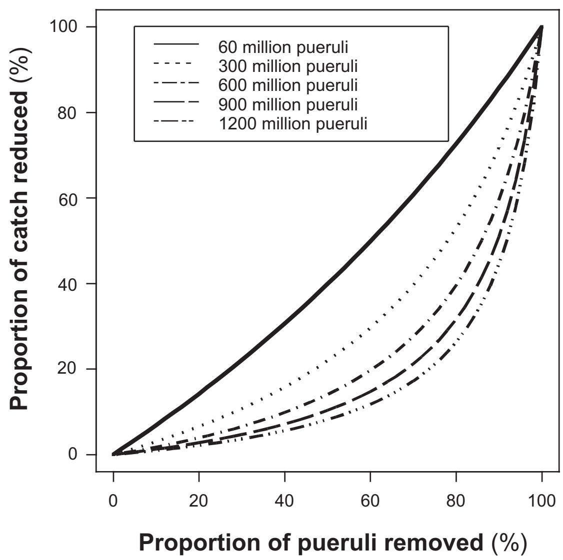

Figure 39. Provides an estimation of the relationship between the removal of *Panulirus cygnus* and the lobster catch reduction , over a range of levels of puerulus settlement.

Table16. Based on model results for the region 29°S to 30°S, the number of *Panulirus cygnus* pueruli per lobsters recruited to the fishery, for different levels of puerulus settlement and proportions of pueruli harvested (p), assuming a constant fishing effort of 2.2819 million pot lifts per season.

	Number of pueruli (millions)																				
p	60	120	180	240	300	360	420	480	540	600	660	720	780	840	900	960	1020	1080	1140	1200	1260
0.00	46	62	78	94	110	126	142	158	174	190	206	222	238	254	270	285	301	317	333	349	365
0.05	48	64	80	96	112	128	144	160	176	191	207	223	239	255	271	287	303	319	335	351	367
0.10	50	66	82	98	114	130	145	161	177	193	209	225	241	257	273	289	305	321	337	353	369
0.15	52	68	84	100	116	132	147	163	179	195	211	227	243	259	275	291	307	323	339	355	371
0.20	54	70	86	102	118	134	150	166	182	198	213	229	245	261	277	293	309	325	341	357	373

Table 16 provides the reference for a given level of puerulus settlement of the modelled number of lobsters per pueruli in relation to the proportion of pueruli harvested. For example, for a puerulus settlement of 900 million, removal of 10% of the pueruli would be expected to result in $\frac{900}{273} = 3.3$ million lobsters being caught by the fishery over two fishing seasons, assuming effort remains constant at 2.2819 million pot lifts per fishing season.

Figure 40 shows that quite different sized puerulus settlements can contribute approximately the same number of lobsters to the fisheries. Hence removal of large number of pueruli would not necessarily dramatically affect the catch of the fishery, assuming that there was a substantial puerulus settlement.

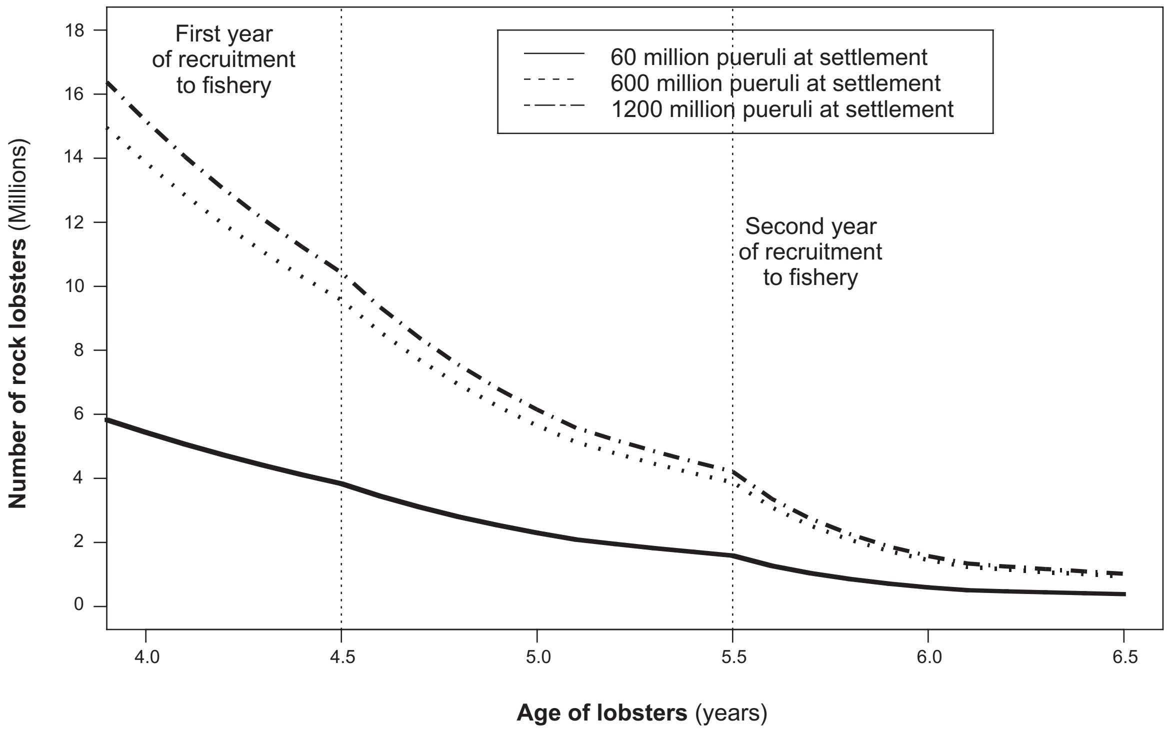

Figure 40. Number of *Panulirus cygnus* available in the region 29°S to 30°S for capture at the time of fishing arising from different levels of pueruli settlement.

Table 17. Estimates of the number of lobsters remaining in the cohort at 4.5 years of age, for different levels of puerulus settlement and removal of pueruli at three different levels of settlement in the 29°S – 30°S region.

Number of pueruli at settlement (millions)	Number of lobsters at the beginning of fishing (millions)	Removal of pueruli (millions)	Number of lobsters at the beginning of fishing (millions)
60	3.83	0.5	3.81
		1	3.79
		5	3.61
		10	3.38
		15	3.16
		20	2.87
		25	2.60
		30	2.30
		35	1.98
600	9.55	5	9.53
		10	9.52
		20	9.49
		40	9.43
		100	9.24
		150	9.05
		200	8.82
		250	8.54
		300	8.19
1200	10.41	10	10.40
		50	10.37
		100	10.32
		150	10.28
		200	10.22
		300	10.10
		400	9.96
		500	9.78
		600	9.55

It can be seen from Figure 39 and indirectly from Table 17, that with a settlement of 60 million pueruli, which equates to the lowest settlement recorded at Seven Mile Beach (Table 7), it would be necessary to remove about 10 million pueruli before recording a greater than 10% reduction in the number of lobsters remaining at the time of first year of recruitment to the fishery (4.5 years after settlement). From Figure 39 it can be seen that as the number of pueruli at settlement increases, so too does the number required to be removed, before the catch is significantly reduced i.e. removal of up to 30% of pueruli for medium to high levels of puerulus settlement (300 to 1200 million pueruli settlement size) would result in a less than 10% reduction in catch.

Using the density-dependent model with $M_d = 0.6696$ and $q_d = 0.0062$, the estimated mortality between the first and second years of settlement is 86% (assuming $N_0 = 600$ million pueruli). This result is not comparable to the result in Section 2, where mortality for years 2, 3, 4, … was assumed to be $M = 0.226$. The attempt in Section 3 to take density dependence effects into account in the model means that the estimated value of

M_d is not comparable with M. However, the model in Section 3 is considered to be a biologically more realistic representation of the early life history of the species than the model in Section 2.

Tables 18-23 give possible catch reductions for different levels of pot lift reduction and puerulus harvesting based on the puerulus settlement levels that have been experienced at Seven Mile Beach over the last 30 years. Throughout we assume that the 100% fishing effort for each fishing season is 2.2819 million pot lifts and any reductions in pot lifts are a reduction of this level of effort.

Table 18. Summary of percentage of reduction in catch in the first year, with the percentage of reduction in pueruli and percentage of reduction in fishing effort based on a population of 60 million pueruli.

% reduction in catch with 60 million pueruli		**% of reduction in pot lifts (fishing effort)**										
		0	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**
% of reduction in pueruli	**0**	**0**	**1.49**	**3.00**	**4.52**	**6.07**	**7.63**	**9.20**	**10.80**	**12.41**	**14.04**	**15.69**
	5	3.36	4.80	6.26	7.74	9.23	10.73	12.26	13.80	15.36	16.93	18.53
	10	6.84	8.23	9.64	11.06	12.49	13.95	15.42	16.90	18.41	19.93	21.46
	15	10.45	11.78	13.13	14.50	15.88	17.28	18.69	20.12	21.56	23.02	24.50
	20	14.18	15.46	16.76	18.07	19.39	20.73	22.08	23.45	24.83	26.23	27.65

Table 19. Confidence bands (±) for percentage of reduction in catch in the first year, with the percentage of reduction in pueruli and percentage of reduction in fishing effort based on a population of 60 million pueruli.

% reduction in catch with 60 million pueruli		**% of reduction in pot lifts (fishing effort)**										
		0	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**
% of reduction in pueruli	**0**	**0**	**1.11**	**2.20**	**3.28**	**4.35**	**5.40**	**6.43**	**7.44**	**8.43**	**9.40**	**10.35**
	5	0.87	1.25	2.15	3.14	4.14	5.14	6.12	7.10	8.05	8.99	9.90
	10	1.71	1.82	2.41	3.21	4.10	5.01	5.92	6.84	7.74	8.63	9.50
	15	2.51	2.50	2.87	3.47	4.20	4.99	5.82	6.66	7.49	8.32	9.14
	20	3.26	3.20	3.41	3.84	4.42	5.09	5.81	6.56	7.32	8.08	8.84

Table 20. Summary of percentage of reduction in catch in the first year, with the percentage of reduction in pueruli and percentage of reduction in fishing effort based on a population of 600 million pueruli.

% reduction in catch with 600 million pueruli		% of reduction in pot lifts (fishing effort)										
		0	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**
% of reduction in pueruli	**0**	**0**	**1.50**	**3.01**	**4.54**	**6.08**	**7.65**	**9.23**	**10.83**	**12.44**	**14.08**	**15.73**
	5	0.85	2.33	3.83	5.35	6.88	8.43	10.00	11.59	13.19	14.81	16.45
	10	1.78	3.25	4.74	6.24	7.76	9.29	10.84	12.41	14.00	15.61	17.23
	15	2.80	4.25	5.72	7.21	8.71	10.23	11.77	13.32	14.89	16.48	18.09
	20	3.92	5.36	6.81	8.28	9.77	11.27	12.79	14.32	15.88	17.45	19.03

Table 21. Confidence bands (±) for percentage of reduction in catch in the first year, with the percentage of reduction in pueruli and percentage of reduction in fishing effort based on a population of 600 million pueruli.

% reduction in catch with 600 million pueruli		% of reduction in pot lifts (fishing effort)										
		0	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**
% of reduction in pueruli	**0**	**0**	**1.10**	**2.20**	**3.27**	**4.34**	**5.38**	**6.41**	**7.42**	**8.41**	**9.37**	**10.32**
	5	0.58	1.14	2.15	3.20	4.24	5.27	6.29	7.28	8.26	9.22	10.15
	10	1.19	1.46	2.27	3.22	4.21	5.21	6.20	7.18	8.14	9.08	10.00
	15	1.85	1.96	2.55	3.37	4.28	5.22	6.17	7.11	8.05	8.97	9.87
	20	2.56	2.57	2.98	3.65	4.45	5.31	6.20	7.10	8.00	8.89	9.77

Table 22. Summary of percentage of reduction in catch in the first year, with the percentage of reduction in pueruli and percentage of reduction in fishing effort based on a population of 1200 million pueruli.

% reduction in catch with 1200 million pueruli		% of reduction in pot lifts (fishing effort)										
		0	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**
% of reduction in pueruli	**0**	**0**	**1.50**	**3.01**	**4.54**	**6.08**	**7.65**	**9.23**	**10.83**	**12.45**	**14.08**	**15.74**
	5	0.47	1.95	3.46	4.98	6.52	8.08	9.65	11.24	12.85	14.48	16.13
	10	0.98	2.46	3.96	5.47	7.00	8.55	10.12	11.70	13.30	14.92	16.56
	15	1.55	3.02	4.51	6.01	7.54	9.08	10.63	12.21	13.80	15.41	17.04
	20	2.17	3.64	5.12	6.61	8.13	9.66	11.20	12.77	14.35	15.95	17.57

Table 23. Confidence bands (±) for percentage of reduction in catch in the first year, with the percentage of reduction in pueruli and percentage of reduction in fishing effort based on a population of 1200 million pueruli.

% reduction in catch with 1200 million pueruli		% of reduction in pot lifts (fishing effort)										
		0	**2**	**4**	**6**	**8**	**10**	**12**	**14**	**16**	**18**	**20**
% of reduction in pueruli	**0**	**0**	**1.10**	**2.20**	**3.27**	**4.33**	**5.38**	**6.41**	**7.42**	**8.40**	**9.37**	**10.31**
	5	0.35	1.09	2.15	3.22	4.27	5.31	6.33	7.33	8.32	9.28	10.22
	10	0.72	1.20	2.17	3.20	4.23	5.25	6.26	7.26	8.23	9.19	10.12
	15	1.13	1.42	2.25	3.22	4.22	5.22	6.21	7.19	8.16	9.10	10.03
	20	1.58	1.74	2.42	3.30	4.25	5.21	6.18	7.15	8.10	9.03	9.94

In Tables 18, 20 and 22 there is a reduction of 6.84%, 1.78 % and 0.98% in recruitment to the fishery for a 10% reduction in 60, 600 and 1200 million pueruli. There is a reduction of 7.63% (60 million pueruli), 7.65% (600 million pueruli) and 7.65% (1200 million pueruli) in catch when there is a 10% reduction in fishing effort. If there is both a 10% reduction in pueruli and fishing effort, the reduction in catches is estimated to be 13.95% (60 million), 9.29% (600 million), 8.55% (1200 million pueruli). Tables 19, 21, and 23 are used to give a 95% confidence interval for the expected catch reduction for a given level of puerulus harvesting and fishing effort reduction. For example, with a 600 million puerulus settlement, a 5% harvesting of pueruli and a 4% reduction in fishing effort would result in a 3.83% (Table 20) reduction in catch and a 95% confidence interval of reduction in catch of 3.83% ± 2.15% (Table 21).

Table 24. The expected percentage reduction in fishing effort (assumed to be 2.2819 million pot lifts per fishing season) required each fishing season to maintain the expected level of contribution to the spawning stock under normal fishing effort and no puerulus harvesting, so as to maintain biological neutrality in the 29°S – 30°S region under different levels of puerulus harvesting.

	Number of pueruli (millions)																			
p (%)	**60**	**120**	**180**	**240**	**300**	**360**	**420**	**480**	**540**	**600**	**660**	**720**	**780**	**840**	**900**	**960**	**1020**	**1080**	**1140**	**1200**
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	5	4	3	3	3	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1
10	10	8	7	6	6	5	5	5	4	4	4	4	4	4	4	3	3	3	3	3
15	16	13	11	10	9	8	8	7	7	7	6	6	6	6	6	6	5	5	5	5
20	23	18	16	14	13	12	11	10	10	9	9	9	9	8	8	8	8	8	8	7

Table 24 indicates the proportional reduction in fishing effort required in each of the two years of recruitment of a particular cohort to the fishery, so as to maintain that cohort's contribution to the 6.5 year old recruits that would have existed had no puerulus harvesting taken place. For example, harvesting 10% of an initial cohort of size 600 million would require fishing effort to be reduced by 4% (or by 0.04(2.2819) = 91.3 thousand pot lifts per year) for each fishing season. The confidence bands for the number of stock remaining at age 6.5 years of age under the puerulus harvesting and fishing reduction policy of Table 24 are presented in Tables 25 and 26.

Table 25. The 95% lower confidence band limit of the level of stock at age 6.5 years (in millions), the expected age of maturity of the western rock lobster. These limits assume the use of the corresponding fishing reduction, for the level of puerulus harvesting and settlement, of Table 24.

	Number of pueruli (millions)																			
p(%)	60	120	180	240	300	360	420	480	540	600	660	720	780	840	900	960	1020	1080	1140	1200
0	0.34	0.50	0.59	0.65	0.69	0.72	0.74	0.76	0.78	0.79	0.80	0.81	0.82	0.83	0.83	0.84	0.84	0.85	0.85	0.86
5	0.33	0.49	0.58	0.64	0.68	0.71	0.73	0.75	0.77	0.78	0.79	0.80	0.81	0.82	0.82	0.83	0.84	0.84	0.84	0.84
10	0.33	0.48	0.57	0.63	0.67	0.70	0.72	0.74	0.76	0.77	0.78	0.79	0.80	0.81	0.81	0.82	0.82	0.83	0.83	0.83
15	0.32	0.47	0.56	0.61	0.66	0.69	0.71	0.73	0.75	0.76	0.77	0.78	0.79	0.79	0.80	0.81	0.81	0.81	0.82	0.82
20	0.31	0.45	0.54	0.60	0.64	0.67	0.70	0.71	0.73	0.74	0.75	0.76	0.77	0.78	0.79	0.79	0.80	0.80	0.81	0.81

Table 26. The 95% upper confidence band limit of the level of stock at age 6.5 years (in millions), the expected age of maturity of the western rock lobster. These limits assume the use of the corresponding fishing reduction, for the level of puerulus harvesting and settlement, of Table 24.

	Number of pueruli (millions)																			
p(%)	60	120	180	240	300	360	420	480	540	600	660	720	780	840	900	960	1020	1080	1140	1200
0	1.39	2.02	2.39	2.63	2.80	2.92	3.02	3.10	3.16	3.21	3.26	3.29	3.33	3.35	3.38	3.40	3.42	3.44	3.45	3.47
5	1.36	1.99	2.35	2.59	2.76	2.88	2.98	3.06	3.12	3.17	3.22	3.26	3.29	3.32	3.35	3.37	3.39	3.41	3.42	3.42
10	1.32	1.94	2.31	2.54	2.72	2.84	2.94	3.02	3.07	3.13	3.17	3.21	3.25	3.28	3.30	3.31	3.33	3.35	3.37	3.38
15	1.28	1.89	2.25	2.49	2.66	2.78	2.89	2.96	3.02	3.08	3.11	3.16	3.19	3.22	3.25	3.27	3.28	3.30	3.32	3.34
20	1.24	1.83	2.20	2.43	2.60	2.72	2.82	2.89	2.96	3.01	3.06	3.10	3.14	3.16	3.18	3.21	3.23	3.25	3.27	3.27

It should be noted that whilst the confidence intervals vary for the number of lobsters at 6.5 years of age (i.e. 5.5 years after settlement) for different levels of puerulus settlement and puerulus harvesting (and hence, fishing reduction), the expected number of lobsters at age 6.5 years for these different parameters are the same i.e. the distributions of the number of lobsters in Table 24 are identical except for the variance. For example, when the puerulus settlement is 60 million, the number of lobsters remaining at age 6.5 years, given that 5% of puerulus have initially been harvested and fishing has been reduced by 5% (Table 24), compared to that if no fishing reduction and puerulus harvesting had taken place, has the same expected level except that the lower bound has reduced by 3% (from 0.34 to 0.33 million, Table 25) and the upper by 2.2% (from 1.39 to 1.36 million, Table 26).

When the puerulus settlement is 600 million, the number of lobsters remaining at age 6.5 years, given that 10% of puerulus have initially been harvested and fishing has been reduced by 4% (Table 24), compared to that if no fishing reduction and puerulus harvesting had taken place, has the same expected level except that the lower boundary has reduced by 1.3% (from 0.79 to 0.78 million, Table 25) and the upper by 2.5% (from 3.21 to 3.13 million, Table 26). In determining the possible number of puerulus to be harvested, Table 25 (lower limit on the number of lobsters at age 6.5 years) warrants serious consideration in that we would want to ensure that the minimum number of lobsters at age 6.5 years under puerulus harvesting and fishing reduction, is not significantly different to what would have existed had harvesting not taken place.

1.3.4 Discussion

Because of the high density-dependent mortality that occurs between settlement of the pueruli and recruitment into the fishery, removal of even large numbers of pueruli will have minimal effect on future catches. As an example (see Table 17), removal of one million pueruli from an initial cohort size of 60 million would lead to only an approximately 1% reduction in the number of lobsters living to 5.5 years after settlement recruiting to the fishery.

The calculations on the number of potlifts which need to be removed to achieve biological neutrality in this analysis, were made only for the 29°S – 30°S latitude area. An analysis of the impact of the 1993/94 management package on the western rock lobster fishery indicated that the effect of pot removals on catches would be similar to the result produced by this model, at least in the first year. It should be noted that reductions in the number of potlifts that are needed to achieve biological neutrality will vary in other regions of the fishery to those used in this study

As already discussed on page 42, the estimated value of $M = 0.226^{-1}$ (Morgan 1977, p. 115) used in Section 2 is questionable. The model $Z = F + M$ was used to estimate M when fishery effort approached zero. Total mortality Z was estimated by using a relationship between growth rate and the average carapace length. The data used for the study were from 1954/55 to 1960/61 and 1967/68 to 1972/73. This was a cross sectional study and not a longitudinal study for estimating M. F was highly correlated with population size in that year and hence, it is highly likely that the error from F is greater than the error for M. Morgan also questioned the estimate, and mentioned the estimates as being derived by Chittlelborough (1970) and Bowen and Chittleborough (1966) (0.222, 0.73). An independent estimate of M for Rat Island (Abrolhos) (Morgan, 1977; p. 113) has a mean of 3.12 year^{-1} and a standard error 0.40. However, this result would also seem questionable.

M would be easier to calculate if there was no fishing in the area. Unfortunately there are no data available for such an analysis. The prediction of M using data affected by fishing effort could lead to the production of a flawed result because M and F are highly correlated. By using data with fishing mortality to estimate M, it is likely that M will be underestimated due to some lobsters having been removed by the fishery before being subjected to predation.

The estimated value of $M = 0.6696$ year^{-1} in this study is considered to be more likely than Morgan's M = 0.226, since:

i) it was estimated using data at puerulus settlement and ages 4 and 5 years (i.e. t = 1, t = 3 and t = 4); and
ii) it was calculated simultaneously with the fishing and density dependent mortality, as compared to Morgan (1977) who calculated these values independently.

However, we would expect that our $M = 0.6696$ year^{-1} may be higher than the true value since we have not included information on lobsters older than 6 years of age.

The estimate for fishing mortality (F=~0.75) is lower than those that have been used by other studies (Walters *et al*. 1993), where they assumed $M = 0.226$, and is more typical of estimates made for periods in the late 1960s and early 1970s (Morgan 1977). The lower fishing mortality for those animals entering the fishery at 3.5 years (F_1) compared to 4.5 years (F_2), after settlement, is due to the first group being captured as reds in the late part of the season, compared to the slightly older group being caught as whites in the early part of the fishing season. The whites animals are known to be more catchable than the reds (Brown and Caputi 1983).

1.4 Summary of puerulus-wild catch biological neutrality information for the western rock lobster

1.4.1 Introduction

A review of the practicality of cultivating pueruli of the western rock lobster, *Panulirus cygnus* in Western Australia was made by Meagher (1994) for the Western Australian Fishing Industry Council. Meagher concluded, "western rock lobster culture appears to be a good commercial prospect". However, "it will not proceed unless the Research and Development program demonstrates that the puerulus harvested and cultured, are excess to those required for maintenance of the existing wild-catch fishery".

The study brief was to examine the impact of puerulus exploitation on the future catches in the wild fishery, and to determine management measures which might be required to maintain 'biological neutrality'. This study was made using existing data on puerulus settlement, juvenile densities and recruitment rates of the western rock lobster. They have been examined to assess the likely effects on the wild fishery that might result from harvesting pueruli for aquaculture purposes. It was not possible within time and available resources to undertake a study of all areas of the western rock lobster fishery. However, data were available to permit examination of the 29°S to 30°S area to test the usefulness of this approach. These latitudes encompass the area between Dongara and Geraldton, which are near the centre of the western rock lobster fishery.

In most circumstances any exploitation of the early life history stages of an animal would be expected to result in some, though probably not proportional, change to the number of animals surviving to larger sizes. With this in mind, we have taken the approach in this study of modelling the likely effect on future wild catches that might be predicted to result from the removal of various proportions of the settlement. A primary aim of sustainability in the western rock lobster fishery is to maintain the reproductive capacity of the breeding stock at a sufficient level to replenish itself. Biological neutrality is in this context, the levels of catch which might need to be forgone to maintain the reproductive capacity of the breeding stock if pueruli are removed for aquaculture. It is not possible to follow the pueruli from settlement right through to the breeding stock. Therefore we have assumed that adjusting the catch to compensate for removals of pueruli for aquacultural purposes will provide sufficient protection of the breeding stock. With the expected age of maturity for lobsters in the Dongara region (the region chosen to examine the question of biological neutrality) being 6.5 years of age, the fishing effort each season must be reduced so that the number of 6.5 year olds under puerulus harvesting is the same under the normal conditions of no puerulus harvesting with normal (no reduction in) fishing effort.

The work covered by this study was in four parts, namely:

1) catch-puerulus relationships;
2) estimating mortality between puerulus settlement and recruitment to the fishery;
3) puerulus mortality model development; and
4) integration of the detailed modelling work in parts 1-3 and discussion of the potential application of the models in estimating levels of puerulus exploitation and their likely effects on catches in the fishery.

The studies undertaken in sections 1-3 provide an understanding of the relationships between levels of puerulus settlement, mortality rates through to recruitment, and the levels of recruits to the fishery arising from different levels of puerulus settlement in the western rock lobster. We present an extended executive summary of the results in this section, and examine their usefulness in understanding the biological neutrality question. We also present data showing catch/weight reductions, which are equivalent to harvestable quantities of pueruli that would achieve biological neutrality in the western rock lobster fishery.

1.4.2 Summary of the results of parts 1–3

Part 1 of this report used fishers' compulsory catch and effort data, fishers' voluntary log book data and long term puerulus settlement data sets from research puerulus collectors moored at the Abrolhos Islands, Dongara, Jurien and Alkimos, all collected by the Department of Fisheries in W A.

The object of this part of the work was to estimate the likely contribution made by particular year classes of pueruli to commercial catches of red and white lobsters in subsequent seasons. In addition, the data were used to derive stock dependent mortality indices for the four areas of the fishery to examine changes in mortality indices in different areas of the fishery.

The model used in this report differed from the power regression approach that has been used in the past (Caputi *et al*. 1995a) in that this model was non-linear. Conclusions from the analysis of the data confirmed what has been reported previously (Caputi *et al*. 1996), namely that:

1. Recruitment into the commercial fishery is most dependent on settlement of pueruli in the coastal reefs taking place three and four years earlier. The contribution to the fishery made by pueruli settling five years earlier was estimated as being small and made little or no difference to the model fit. As a consequence of this result, all further calculations in this document have assumed that recruitment to the commercial fishery was entirely dependent on pueruli that settled three and four years earlier.
2. That the contribution made by 'red' lobsters recruiting to the fishery three years after settlement, compared to 'whites' recruiting four years after settlement is different in the four regions that were examined. The percentage contribution made by red (three year old) lobsters is highest at the Abrolhos Islands, followed by the north coastal areas.
3. Stock dependent mortality coefficients showed the highest stock-dependent natural mortality coefficient at the Abrolhos Islands followed by the northerly coastal areas. The important outcome of this result, is that it is clear that if pueruli are to be harvested in the future, that because of the different contributions to the fishery made by pueruli settling three/four years before recruitment in different regions, and because of differences in stock dependent mortalities in different regions, these factors will need to be taken into account in establishing harvesting procedures.

Part 2 of this report was an analysis of the rates of survival between settlement of the pueruli and recruitment into the fishery.

To achieve this, it was necessary to have a measure of the absolute abundance of the pueruli, which could be linked with the subsequent catches of recruits.

CSIRO data on the density of puerulus settlement (numbers/m^2) in different types of benthos was available from Seven Mile Beach (which is between Dongara and Geraldton, in the centre of the western rock lobster fishery) for 1987/88 and 1988/89. Published data from this study showed that settlement, with the exception of two individual pueruli (Jernakoff 1990), was virtually exclusively on limestone reefs (Fitzpatrick *et al.* 1989). Puerulus settlement on a series of reefs from subtidal to 20 m, was monitored on four separate occasions each year of the period February 1987 to March 1989. These data showed that at least some settlement took place down to 30 m.

These two years of puerulus settlement data at Seven Mile Beach were used to estimate the number of pueruli/m^2 that would have been likely to have settled over those years between 29°S and 30°S (an area encompassing the Seven Mile Beach study site, but approximately seven times larger). To do this, aerial mapping techniques were used to identify all the hard surface areas within the 29°S to 30°S area to a depth of 20 m (Conservation and Land Management, Western Australia). The total surface area of this type of habitat between the shore and 20 m was estimated to be 382.3 million m^2.

The number of pueruli and juveniles present in the 382.3 million m^2 area each month was estimated by multiplying the mean puerulus settlement density as calculated, based on surface area for that month by 382 million m^2 and the amount of ground available between 29°S and 30°S to a depth of 20 m.

Pueruli and early juveniles <25 mm CL were shown in the study by Jernakoff (1990) to be very selective in the choice of their shelter. These were animals from 8.2 mm at settlement and early juveniles, up to seven months after settlement. Most were solitary, chose deep rather than shallow holes and selected holes related to their carapace size (Jernakoff 1990). From these observations, it might be assumed that though there were limited settlement sites during the season, the availability of these sites could be considered to be a dynamic process, with new sites continually becoming available as pueruli/juveniles moulted and needed to select larger holes. Since settlement occurs over a prolonged period in the Seven Mile Beach region (i.e. about 80% occurs between August and December), we have assumed that the available holes permitted two full settlements each season and that therefore, the number settling over each year covered by the CSIRO study was equal to:

> 2* (mean density/m^2 for November and March over a particular season) *(382.3 million m^2).

Data on recruitment to the western rock lobster fishery were available from fisher logbooks and compulsory catch and effort returns collected by the Department of Fisheries in WA.

The mortality rate between settlement and recruitment to the fishery was determined by dividing the number of recruits to the fishery in a particular season by the estimated puerulus settlement that gave rise to that recruitment. For the 1987/88 season, the estimated mortality was 98.11%, and for the 1988/89 season, 98.52%. In estimating these mortalities we assumed that there was constant mortality from year two after settlement onwards. This is unlikely to be the case and we therefore believe these estimates to be the upper limit of mortality in the first year. Modelled estimates of population depletion over time, based on the output from section 2, are presented in Figures 41 and 42.

To investigate further the mortality between the first year on the nursery reefs (puerulus settlement) and the second year, we assumed that the mortality rate (M = 0.226 $year^{-1}$, Morgan (1977)) was constant from the second year onwards through to recruitment. Under this scenario, it was found that the mortality for the first year after the settlement (age =1 to

2) was 97.1% for the 1987/88 puerulus settlement, and 98.7% for the 1988/89 puerulus settlement. This means, that of the number settling as pueruli, only 2.3-3% survive their first year in the nursery reefs. This is illustrated in Figures 41 and 42.

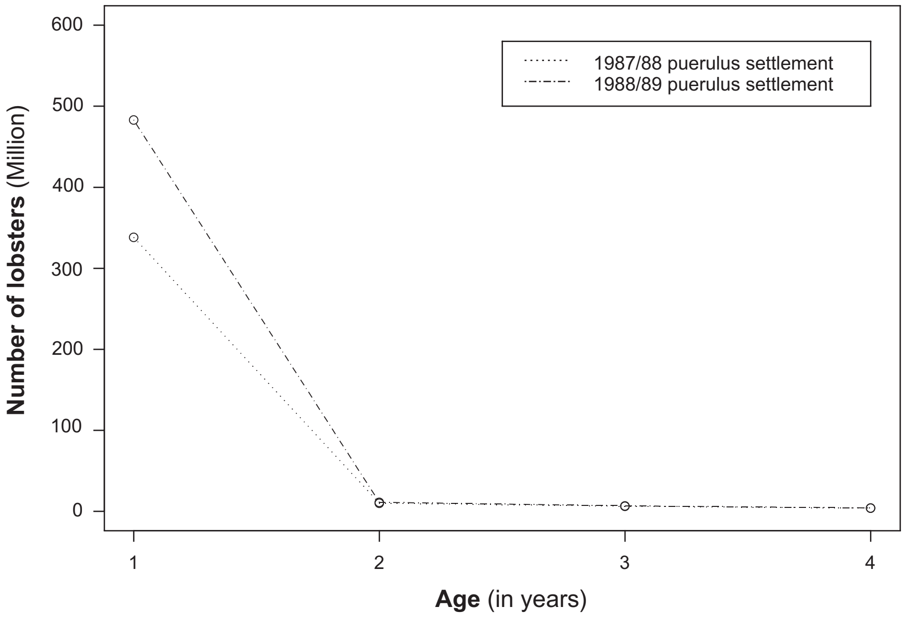

Figure 41. Depletion of *Panulirus cygnus* pueruli and juveniles from settlement (age 1 years) to age 4 years for the 1987/88 and 1988/89 settlement seasons. Estimate made using a constant mortality rate between years 2 to 4.

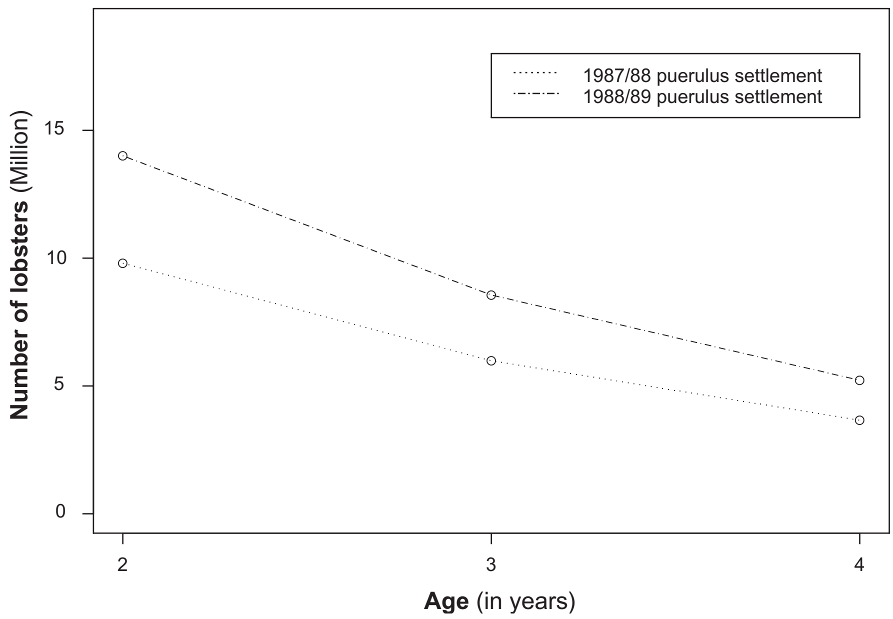

Figure 42. Depletion of *Panulirus cygnus* pueruli and juveniles from age 2 years to age 4 years, for the 1987/88 and 1988/89 settlement seasons. Estimate made using a constant mortality rate between years 2 to 4.

Part 3 of this report made use of the data from parts 1 and 2. However, a difference was that the mortality was modeled to decline with age rather than be constant after the first year (as in part 2 of this report). This change is considered to be biologically more defensible. As a result of this change, mortality in year one decreased from 97-98% to about 80% (79.8% for the 1987/88 settlement and 83.9% for the 1988/89 settlement). This is inline with Caputi *et al.* (1996) and Section 1 which show the relationship between catch and puerulus index leveling off between medium and high levels of puerulus settlement. This would be particularly applicable to the Dongara and Abrolhos region.

Using these data a model was developed to examine the likely impact that harvesting pueruli might have on the catches in the wild fishery. The model focused on the area between 29°S and 30°S, for which there was data available, and simulated the outcome of harvesting pueruli under various settlement levels (densities) within the range that has been experienced over the 30 year period that settlement collectors have been in place at Seven Mile Beach.

Because of the high density dependent mortality that occurs between settlement of the pueruli and recruitment into the fishery, removal of a significant percentage (up to 30%) of pueruli for medium to high levels of puerulus settlement (300 to 1200 million puerulus settlement size) would result in a less than 10% reduction in catch (Figures 43 and 44).

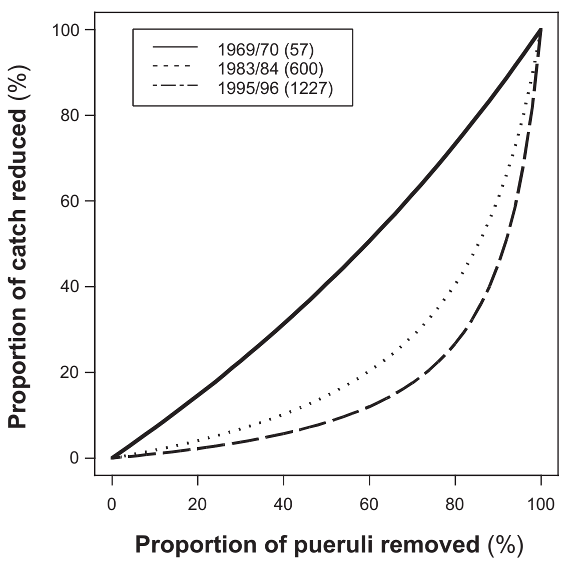

Figure 43. Effect of proportion of pueruli of *Panulirus cygnus* removed against proportion of recruitment to the fishery reduced at three levels, at the highest, lowest, and a medium level of puerulus settlement recorded in the 29°S to 30°S region (shown in brackets).

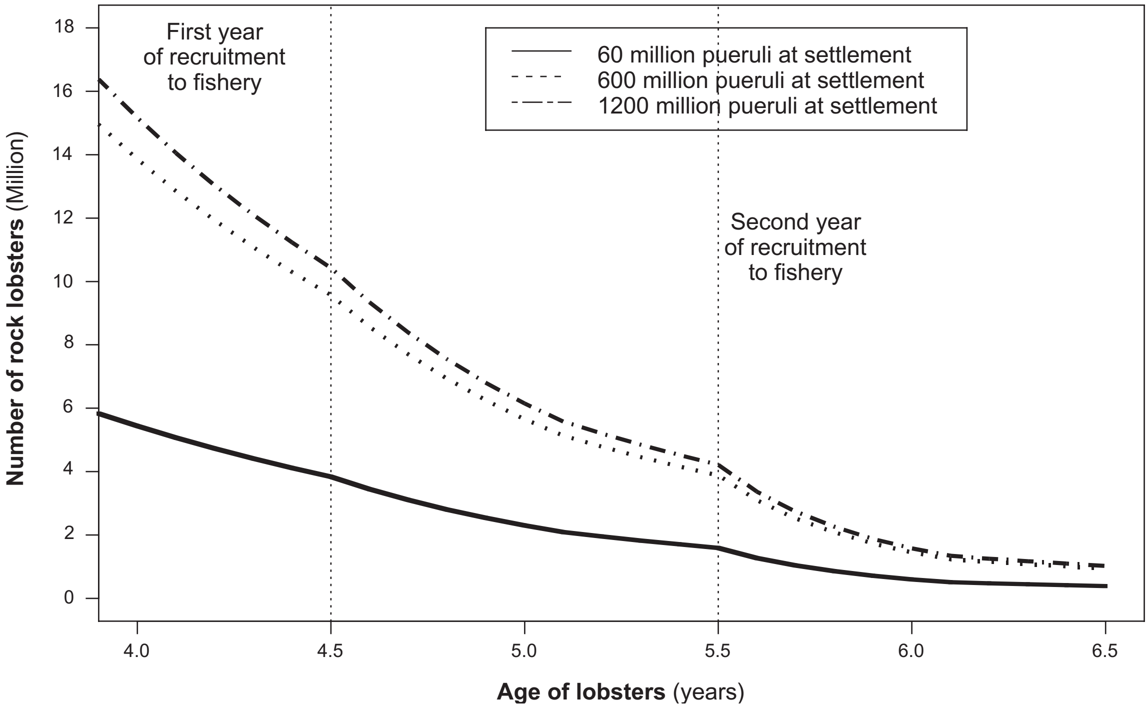

Figure 44. Number of *Panulirus cygnus* available in the 29° – 30°S region for capture at the time of fishing arising from different levels of puerulus settlement.

In Table 27 (a repeat of Table 17) we have presented estimates of the effect that removal of pueruli would have on future levels of recruitment to the fishery, arising from settlement (low, medium and high) in the 29°S – 30°S region. Table 27 has assumed that puerulus settlement occurs uniformly over the entire 382 million m^2 of reef area considered suitable for puerulus settlement in the 29°S – 30°S region. It is possible that some may feel that the amount of reef area suitable for settlement by pueruli may have been overestimated. Tables 28-29 illustrate that even if the amount of reef area suitable for settlement was half (Table 28) or a quarter (Table 29) of what was estimated to be the case in Table 27, that this would not greatly affect the estimates of future levels of recruitment to the fishery. For instance, for the lowest level of puerulus settlement that has been experienced, the estimated number of lobsters at the beginning of fishing when the area is halved (3.59 million lobsters, Table 28) would be 6% less than that estimated when the whole area was used (3.83 million lobsters, Table 27). If the area estimate between 29°S – 30°S was only a quarter of what was estimated in Table 27, then the estimated number of lobsters at the beginning of fishing would have been an estimated 3.38 million lobsters or 12% less than that estimated when the larger area was used (Table 27). Removal of pueruli from either of the simulations in Tables 28 and 29, would not lead to a very different outcome to that provided in Table 27.

Table 27. Estimates of the number of lobsters remaining in the cohort at 4.5 years of age, for different levels of puerulus settlement and removal of pueruli at three different levels of settlement in the 29°S – 30°S region. This table is constructed assuming a uniform density of puerulus over the 382 million m^2 of reef area considered suitable for puerulus settlement in the 29°S – 30°S region.

Number of pueruli at settlement (millions)	Number of lobsters at the beginning of fishing (millions)	Removal of pueruli (millions)	Number of lobsters at the beginning of fishing (millions)
60	3.83	0.5	3.81
		1	3.79
		5	3.61
		10	3.38
		15	3.16
		20	2.87
		25	2.60
		30	2.30
		35	1.98
600	9.55	5	9.53
		10	9.52
		20	9.49
		40	9.43
		100	9.24
		150	9.05
		200	8.82
		250	8.54
		300	8.19
1200	10.41	10	10.40
		50	10.37
		100	10.32
		150	10.28
		200	10.22
		300	10.10
		400	9.96
		500	9.78
		600	9.55

Table 28. Estimates of the number of lobsters remaining in the cohort at 4.5 years of age, for different levels of puerulus settlement and removal of pueruli at three different levels of settlement in the 29°S – 30°S region. This table is constructed assuming a uniform density of puerulus over only half of the 382 million m^2 of reef area considered suitable for puerulus settlement in the 29°S – 30°S region.

Number of pueruli at settlement (millions)	Number of lobsters at the beginning of fishing (millions)	Removal of pueruli (millions)	Number of lobsters at the beginning of fishing (millions)
30	3.59	0.2	3.57
		0.5	3.55
		1	3.51
		1.5	3.47
		2	3.42
		4	3.26
		6	3.08
		8	2.89
		10	2.69
300	8.97	5	8.95
		10	8.92
		15	8.89
		20	8.87
		25	8.84
		30	8.81
		50	8.68
		100	8.28
		150	7.69
600	9.79	5	9.78
		10	9.77
		20	9.76
		40	9.73
		100	9.61
		150	9.50
		200	9.36
		250	9.19
		300	8.97

Table 29. Estimates of the number of lobsters remaining in the cohort at 4.5 years of age, for different levels of puerulus settlement and removal of pueruli at three different levels of settlement in the 29°S – 30°S region. This table is constructed assuming a uniform density of puerulus over only one quarter of the 382 million m^2 of reef area considered suitable for puerulus settlement in the 29°S – 30°S region.

Number of pueruli at settlement (millions)	Number of lobsters at the beginning of fishing (millions)	Removal of pueruli (millions)	Number of lobsters at the beginning of fishing (millions)
15	3.38	0.2	3.35
		0.5	3.30
		1	3.22
		1.5	3.14
		2	3.06
		4	2.72
		6	2.34
		8	1.91
		10	1.44
150	8.49	5	8.44
		10	8.39
		15	8.33
		20	8.27
		25	8.21
		30	8.15
		40	8.00
		50	7.83
		60	7.63
300	9.27	5	9.25
		10	9.24
		15	9.22
		20	9.21
		25	9.19
		30	9.17
		50	9.10
		100	8.86
		150	8.49

The impact of puerulus removals on subsequent catch was estimated to be minimal except in the case of removal of very large numbers of pueruli. However, it would also be possible to counter these losses by effort reductions, and a set of tables allowing calculation of these reductions is provided (Table 30).

Table 30. The expected percentage reduction in fishing effort (assumed to be 2.2819 million pot lifts per fishing season) required each fishing season to maintain the expected level of contribution to the spawning stock under normal fishing effort and no puerulus harvesting, so as to maintain biological neutrality in the 29°S – 30°S region under different levels of puerulus harvesting.

	Number of pueruli (millions)																			
p (%)	**60**	**120**	**180**	**240**	**300**	**360**	**420**	**480**	**540**	**600**	**660**	**720**	**780**	**840**	**900**	**960**	**1020**	**1080**	**1140**	**1200**
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	5	4	3	3	3	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1
10	10	8	7	6	6	5	5	5	4	4	4	4	4	4	4	3	3	3	3	3
15	16	13	11	10	9	8	8	7	7	7	6	6	6	6	6	6	5	5	5	5
20	23	18	16	14	13	12	11	10	10	9	9	9	9	8	8	8	8	8	8	7

If for example, it was decided to permit the harvesting of 20 million pueruli from the 29°S – 30°S latitude area, in a year when puerulus settlement was average (i.e. 600 million), and it was deemed desirable to reduce pot numbers to compensate for these puerulus removals, it would be necessary to remove approximately 1% of the effort in the 29°S – 30°S latitude area to achieve biological neutrality. This converts to a reduction in fishing effort of approximately 23,000 potlifts for the season.

1.4.3 Discussion

The results clearly show that there is a very high mortality between the time of puerulus settlement in the coastal reefs and the time the lobsters move offshore and recruit into the fishery. The estimated mortality during the first year after the settlement (from ages 1-2 years) for *P. cygnus* is estimated to be either as low as 80% or as high as 97%. Assuming the two years of data that were available are typical, only very small numbers of the settling pueruli survive to recruit into the fishery at about 4.5 years of age.

The data on mortalities in other species of rock (spiny) lobsters are sparse, but consistent with the results we have obtained in this study. Marx (1986) and Herrnkind and Butler (1994) have estimated that the natural mortality in the first year after settlement of *P. argus* (a warm-water rock lobster similar to *P. cygnus*) approaches 97%, i.e. only 3% survive to recruit into the fishery. Independent estimates of survival of *P. argus* based on mark recapture of microwire tagged animals were similar, with the range 0.64-4.1% (Herrnkind and Butler 1994).

Actual mortality of settling pueruli may be even higher than what has been estimated by this study. Booth (1999) has observed, both under laboratory and field conditions, that a proportion of southern rock lobster (*J. edwardsii*) pueruli in New Zealand fail to conceal themselves during daylight, even when there is suitable substrate and cover available. The reason for this counter intuitive behaviour is unexplained, and while such pueruli might be suitable for ongrowing, they would not survive long in the wild.

No natural survival estimates have been published for cool water lobsters such as *Jasus edwardsii* in New Zealand. However, unofficial estimates (P. Breen,(National Institue of Water and Atmospheric Research) pers. comm.) indicate that conservative estimates of survival are 25% for year 1 after settlement, 75% for years 2 and 3, and 90% for subsequent years. The older the lobster, the lower the natural mortality.

The calculations on the number of potlifts which need to be removed to achieve biological neutrality in this analysis, were made only for the 29°S - 30°S latitude area. An analysis of the impact of the 1993/94 management package on the western rock lobster fishery indicated that the effect of pot removals on catches would be similar to the result produced by this model, at least in the first year. It should be noted that reductions in the number of potlifts that might be needed to achieve biological neutrality will vary in other regions of the fishery to those used in this study

1.4.3.1 How good are the data on which the estimates are made?

It is inevitable that in a study such as this, dealing with major processes over periods of decades, it has been necessary to make a large number of assumptions in the calculations. It is important that the assumptions that have been made should be clear to the reader and that the sensitivity of the results to those assumptions should be described. It should also be noted that the data collected were not for the purpose for which they have been used in these analyses.

There is little doubt that the strongest and boldest assumptions had to be made in Part 2 of this document. We have put much faith in the reef density estimates of pueruli and juveniles made by CSIRO divers during the 1987/88 and 1988/89 seasons, and believe these to be reliable. These figures are probably conservative as they are based on data on the number of pueruli observed by divers. The limestone reefs in which they were located may contain other caves and ledges in which divers cannot observe the pueruli and young juveniles.

The reef density estimates, which were estimated by bathometric contour lines from CALM satellite imagery data are likely to be much less accurate, and whether the juvenile lobster densities calculated in the Seven Mile Beach area can be extrapolated over the larger 29°S – 30°S region is also debatable. However, despite all these potential errors in calculating absolute abundance of pueruli settling between 29°S – 30°S the most critical assumption is the mortality rate in the first year after settlement.

The levels of settlement of *P. cygnus* pueruli CSIRO has observed (0.1778-1.3076 per m^2) (Table 6, Section 2) are similar or higher than *P. argus*, the only other species for which there are comparative data. Marx (1986) reported that the density of settling pueruli ranged between 0.03 and 1.9 /m^2. However, even at the lowest settlement level of 0.03/m^2, substantial productivity of recruits to the local fishery can occur.

M. Butler, Dept. of Biological Sciences, Old Dominion University, Norfolk, Virginia 23529-0266, USA, (*pers. comm.*) has found that the post-pueruli of *P. argus* are very flexible in their use of habitat. At times of high density they will make use of “less than perfect” shelter, allowing considerable numbers to survive. Clearly if numbers of pueruli are removed from an area, this allows the remaining post-pueruli to make use of the best shelter and other resources. It is not known if *P. cygnus* exhibits this flexibility. However, we do know that in years of high settlement, fishers report considerable numbers of post pueruli in their pots which have been set in deeper water. This means that the levels of puerulus settlement used in our analyses may be conservative, and that at times of high puerulus settlement even greater levels of settlement may occur than we have recorded.

The assumption most likely to affect estimates of *M* in year 1 after settlement or the puerulus to legal size lobster ratio is the estimates of recruiting lobsters (which are calculated indirectly from factory processing and compulsory fisher log books and length monitoring data) and estimates of the natural mortality of sub-legal animals 2 to 3 years after settlement. In the latter case the commonly used natural mortality figure $M = 0.226$ year^{-1} (Morgan 1977) has been assumed to apply for the smaller sizes in the same way that it is accepted as applying to legal sized lobsters (Walters *et al*. 1993).

By good fortune, since it has provided a good contrasting result, the number of pueruli estimated to have settled in 1988/89 was nearly 50% higher than those estimated to have settled in 1987/88 (483 million compared to 338 million), while the estimate of recruits available to the fishery surviving from those years was not nearly as marked (6.4 million from 1987/88 settlement and 7.1 million from 1988/89 settlement).

We chose throughout this investigation, to model the lobster fishery pre-1992 and not to bring in the management changes that occurred after that time. This decision was made because the management changes introduced at that time which (Chubb and Barker 2000) protected certain size classes and mature females and would therefore have complicated comparison with earlier data. Though the changes could have been taken into account, it was not believed that data for the additional years (1993-1999) would have improved the accuracy of the model output.

1.4.3.2 How will removal of pueruli affect the wild catch in a particular area?

At this time the preliminary results of our attempts to design methods to catch large numbers of pueruli (Phillips *et.al.* submitted) suggest that the pueruli will be easiest to catch near the shore, and in selected locations with fringing reefs. This means that the removals would not take place evenly over the whole settlement area. The effects of removals in a small area is unknown, but could be examined.

At least one area in the Western Rock Lobster Fishery, South Passage Shark Bay, presents an unusual situation. Puerulus settlement levels, as recorded on collectors in this area, are generally high by comparison with settlement at other sites along the coast. However, there is only a very small commercial fishery in this area. This may be an area to test puerulus removals for aquaculture without any possibility of disruption to the wild commercial fishery in this area.

1.4.3.3 What about the ecology of the reefs if large numbers of pueruli are removed?

A study carried out at Seven Mile Beach showed that pueruli and post-pueruli of *P. cygnus* are mainly eaten by small fish including *Psannapera waigiensis* (sand bass), *Pelsarta humeralis* (sea trumpeter), *Pseudoabris parilis* (brown-spotted wrasse) and *Plectorhyncus flavomaculatus* (gold-spotted sweetlips) (Howard 1988). None of these fish are commercial species and therefore little is known of their biology.

What do these fish eat if pueruli are removed for aquaculture? All of the fish species discussed above do not live exclusively on rock lobster pueruli. They will presumably adjust their diet based on the number of rock lobster pueruli available. We already know from the collector data that the annual levels of puerulus settlement vary considerably; hence the predators are already used to these kinds of fluctuations, and can respond appropriately.

1.4.3.4 How could the estimates be improved and expanded to cover the whole fishery?

There are several areas where additional research would improve the estimates made in this report.

1) The use of the levels of settlement on the collectors as measures of the natural levels of settlement is based on only two years of data.

   A research program based on using an artificial surface with suitable sized holes, and with a defined pattern, could be monitored over a number of years and provide an improved measure of the natural settlement, leading to improved data on which more accurate modifications can be made to the collector information.

   This would be a particularly useful piece of information, as it would both improve the estimates in 29°S – 30°S and allow the use of the collector data from other sites to be utilized. Not only would such information be useful for assessing possible removals of pueruli for aquaculture, but it would also be useful in managing the wild stocks for the western rock lobster fishery.

2) No data on natural levels of settlement is available from any site other than Seven Mile Beach.

   The research program described in (1) could be expanded to cover other areas of the fishery.

3) A study of the effect of localised removals of pueruli on the ecology of the fish populations in the reef areas could be undertaken. However, this would be difficult to undertake and may not produce useful data given the numbers of pueruli that are likely to be harvested.

4) The results presented in this report could be confirmed by a program to examine the effects of localised pueruli removals on the catches of the fishery in the same area. This would be undertaken most economically as part of the monitoring of any program of removal of pueruli for aquaculture.

5) As noted, the assumed mortality estimates of animals in their second and third year after settlement would undoubtedly be the greatest source of error in estimating the likely mortality rate in the first year after settlement. Mortality estimates for animals in their first year could be improved by very specific studies (e.g. of the kind discussed by Herrnkind and Butler (1994) and Acosta and Butler (1997)) targeting these pre and recently settled juveniles. Research into settling and early post settlement animals is labour intensive and would be expensive to undertake.

1.4.4 Conclusions

All available data that were considered useful for quantifying the likely impact of harvesting western rock lobster pueruli in the wild have been examined and analysed in this report.

Several models are being evaluated to examine the effect of puerulus removals on future recruitments to the fishery. A brief synopsis of the results is as follows:

1) Very high mortality occurs between the time of settlement of the pueruli and recruitment in the fishery. The mortality in the first year after settlement is estimated to be either as low as 80% or as high as 97%, depending on which model is used.

2) Because of high density dependence mortality of the lobsters in the nursery reefs from settlement to recruitment into the fishery, in most years removal of pueruli would have little impact on the levels of recruitment to the fishery.

3) In the example used for this study (the coastal region between 29°S–30°S) at low to medium levels of puerulus settlement, pueruli removals of up to 10% of the number settling will have minimal effect on recruitment to the fishery. At the lowest levels of settlement that have been recorded in the fishery, removals of 500,000 to 5 million pueruli would have had little impact (~6%) on the levels of recruitment to the fishery in that area. However, at low levels of puerulus settlement, higher levels of removals could have a greater effect. For example removal of 20 million pueruli would reduce recruitment to the fishery by about 25%.

4) The impact of puerulus removals on subsequent catch was estimated to be minimal except in the case of removal of very large numbers of pueruli. However, it would also be possible to counter these losses by effort reductions, and a set of tables allowing calculation of these reductions is provided. For example, the removal of 20 million pueruli in an average settlement year in the coastal region between 29°S–30°S, could be compensated by effort reductions of 100 pots (or approximately 22 t). This would achieve biological neutrality. In a rock lobster fishery managed by quota restrictions, it would obviously be easy to calculate the amount of quota that needed to be set aside to compensate for puerulus removals.

5) The effort removals to compensate for removals of pueruli will stabilise the breeding stock at current levels, as similar numbers of animals will reach maturity, as is currently the case.

6) If commercial harvesting of pueruli was to be permitted, it would probably have to be subject to a compensatory reduction in commercial catch, to achieve effective biological neutrality. Such a strategy could be implemented. Most settlement takes place between September/October, which would allow compensatory catch reductions to be calculated before the start of the commercial rock lobster fishing season. However, the reductions could be implemented in subsequent seasons.

7) In some other areas of the fishery (e.g. Abrolhos Islands, and/or possibly South Passage, Shark Bay) which have higher density dependant mortality rates than other areas, harvesting pueruli would have even less effect on the level of animals recruiting to the fishery than in other areas.

2. CHAPTER 2
Commercial puerulus collector trials for *Jasus edwardsii* in Tasmania

2.1 Introduction

Aquaculture in Tasmania is worth an estimated $100 million per annum, and is currently expanding at over 10% per annum (ABARE 2001). Interest in the development of southern rock lobster (*Jasus edwardsii*) culture is considerable. There are two potential sources of seed for *J. edwardsii* aquaculture, larval culture and collection of early settled juveniles from the wild. The production of seed through larval culture is not commercially feasible at present. However, puerulus settlement can be quite high in Tasmania, which provides potential for the development of an industry initially based on that seed source. Recently, the Tasmanian Government issued seven annually renewable permits for collection and ongrowing of 50 000 *J. edwardsii* pueruli. The permits allow for puerulus to be collected from the 1st July 2001.

Puerulus settlement has been routinely monitored in Tasmania since 1991 (Kennedy 1994, Gardner *et al.* 1998). This research has provided information on possible productive collection areas, and types of collectors to use. Following a series of collector design trials around southern Australia (Kennedy *et al.* 1991) crevice collectors (Booth and Tarring 1986) were chosen for routine monitoring for fisheries research. The research also examined the use of collectors positioned near the surface and on the seafloor. While it was concluded that designs on the sea floor catch most *J. edwardsii* puerulus, only a single design, the pallet collector (Lewis 1977) was tested in both positions.

The focus of past collector trials for routine puerulus monitoring was on maximising yield and minimising catch variability. The focus for industry collectors must be on minimising the cost of collection. A previous trial (Mills *et al.* 2000) showed that the Mills (mesh) collector (see Chapter 3, Fig. 64) caught more pueruli, was cheaper to build and easier to handle than other designs.

Ongoing puerulus settlement monitoring has also provided invaluable information about temporal trends in settlement. In most years, two clear peaks in settlement are seen, generally centred around August/September and December/January. These peaks persist in all areas of the state, although their relative magnitude may vary.

The development of commercial puerulus collectors has been undertaken in Tasmania over the past 3 years, supported predominantly by the State Government. Collector designs have been developed around information from past collector trials, extensive surveys of commercial aquaculture facilities, and observations by scientists in the field. This project aims to build on those results, by further developing puerulus collector designs and servicing protocols for *J. edwardsii*.

2.2 Methods

1) Collector design trial

Previous research has shown that the Mills (mesh) collector was an efficient and cheap collector design (Mills *et al.* 2000). This trial aimed to further examine the design of collectors, paralleling research undertaken with *P. cygnus* in Western Australia (reported in Chapter 3). Three collector designs were compared: sandwich collectors and Mills collectors were constructed as outlined in Chapter 3. A third design, the 'bottlebrush' collector, was designed on the observation from industry that mature mussel lines are a good settlement substratum. The basis of the "bottlebrush" collector is a number of 'elements' constructed of flexible material, folded concertina-style, and gathered at their centre. These elements can be affixed to rope or solid rod such as dowel or P.V.C conduit. For the purposes of these trials, each collector comprised 10 elements made from a 180 x 40 cm strip of black windbreak mesh ("Sarlon Industries Pty. Ltd." product no. 648030) (Figure 45). This mesh is similar to that commonly used in onion bags. Each element was folded approximately 20 times and affixed to 15 mm polypropylene rope with a cable tie.
A 6" polystyrene float was attached to each collector to hold it in the water column.

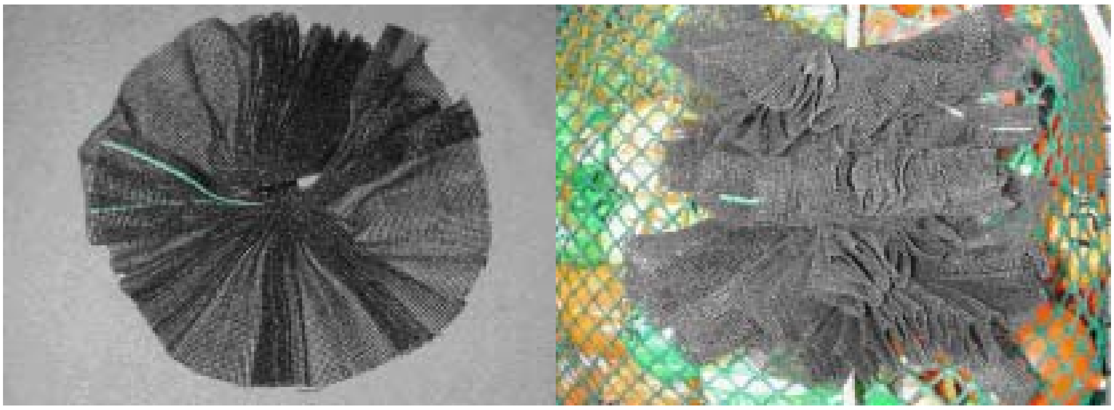

Figure 45. Several elements (left) are cable-tied to a rope to make up a single bottlebrush collector (right).

Collector trials were conducted at Waubs Bay, Bicheno, on Tasmania's east coast (Figure 46). Puerulus settlement has been monitored monthly at this site since 1991, providing useful catch history information. Settlement at Bicheno is generally the highest of five sites regularly monitored around Tasmania (Gardner *et al.* 1998). There is convenient boat access to the bay, and it provides shelter from winds from S to NW quadrants, although it often experiences heavy swell action from the N or NE. As much of the area allocated for commercial collection is on exposed coastline, this represents a realistic trial site for commercial collectors.

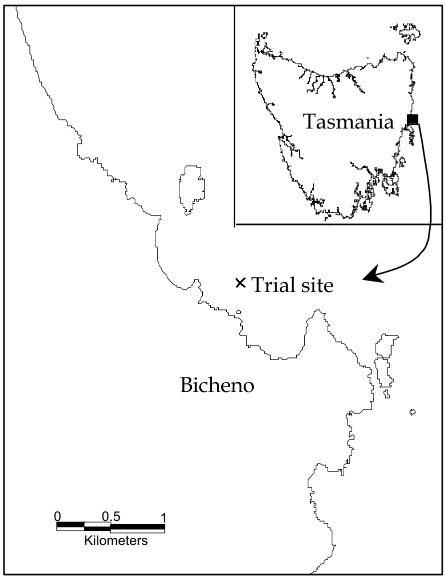

Figure 46. Site of collector trials near Bicheno on Tasmania's east coast.

Collectors were deployed in 10-12 m of water on mooring blocks in place from past experiments. The moorings consisted of car tyres filled with concrete and steel, placed in an 'X' formation on the sea floor. Each of the 4 arms of the 'X' comprised 4 mooring blocks spaced evenly over 20 m. Collectors were attached to a chain between moorings by 1 m rope strops and a stainless steel shark clip and floated approximately 1.5 m above the sea floor.

Ten collectors of each type were deployed for this design trial, as well. Collectors were distributed randomly on the site, and re-randomised twice during the trial, reducing any confounding effects of position on the site or type of adjacent collectors.

Collectors were deployed in April 2000 to allow 3 months conditioning prior to commencing the experiment in August, then serviced monthly. Collectors were first cleared in July, but these data were not included in analyses, as they represent catch over the 3 months of conditioning.

A diver and boat crew working from a 6.1 m aluminium tri-hull vessel serviced collectors. The diver sent collectors up a rope attached at the centre of the site. Collectors were cleared on the boat and attached to steel weights to return them to the site, where the diver reattached them to the ground chain.

2) Long-line trial

Variation in construction material of Mills collectors may alter catch rates. Early trials of substratum types for puerulus settlement (Mills unpub. data) showed that heavy gauge blue polyethylene netting (orange roughy trawl net) was not as effective at catching pueruli as was light-gauge black net. If external cage mesh of collectors is too fine, it may prevent pueruli from entering the collector, particularly where heavy fouling is present. Conversely, cage mesh of similar size to newly settling pueruli may increase retention rates of collectors if pueruli moult in the collector and can no longer pass through the mesh.

Collectors were set on a mid-water long-line (Fig. 47). Up to 300 pueruli had been collected from scallop spat collector lines of similar size, deployed near Maria Island, eastern Tasmania. The external mesh size of these spat bags was less than 2 mm, so all pueruli collected were from the outside of bags. Providing bags with appropriate size external mesh and suitable internal substrata should increase these catch rates.

Collector construction was compared in an orthogonal design with 3 internal mesh colours (black, white and orange) and 3 external mesh sizes (12, 20 and 40 mm). Each combination was replicated 12 times, and 2 spare collectors of each design were deployed in case of loss or damage, giving 126 collectors. Effect of internal mesh type/size was investigated in a parallel trial involving 12 replicates of three mesh sizes (monofilament anti-bird mesh, 48 ply polyethylene 'market trawl' netting and heavy-gauge orange roughy trawl netting), within 20 mm cages. Collectors were randomly assigned to 36 droppers, each dropper holding 4 collectors and attached to a rope backbone floated 5 to 10 m subsurface. The longline was deployed and serviced by a chartered vessel equipped for hauling scallop spat collector lines (Fig 48).

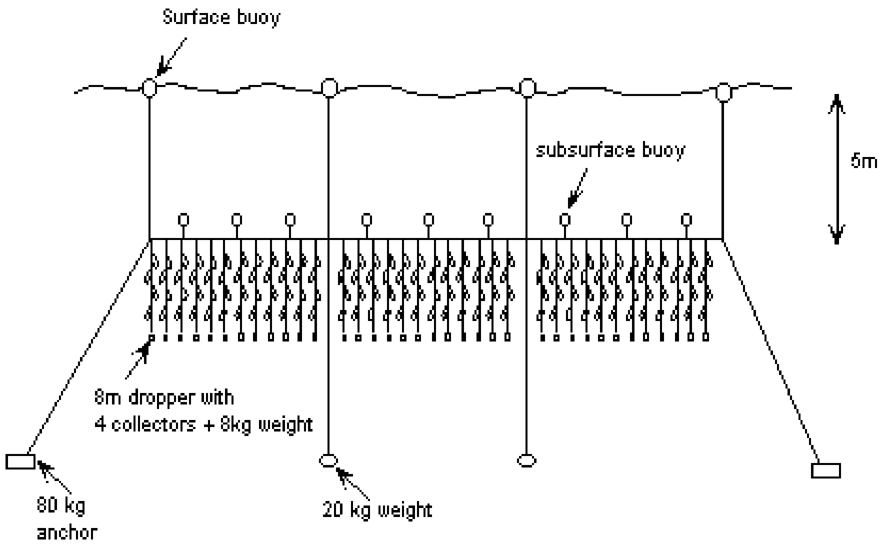

Figure 47. Structure of long-line used for collector trials.

Figure 48. Mesh collectors loaded onto the vessel 'Morning Star' prior to being deployed.

The longline was initially deployed in Mercury Passage inside Maria Island (Fig. 49, site 1), and later moved further north to Grindstone Point (Fig. 49, site 2). Both sites have proven productive in the past and scallop spat lines in this area have been a major source of pueruli for ongrowing trials at the Tasmanian Aquaculture and Fisheries Institute (TAFI). Puerulus collectors were deployed at the same depth and in the same manner as scallop lines.

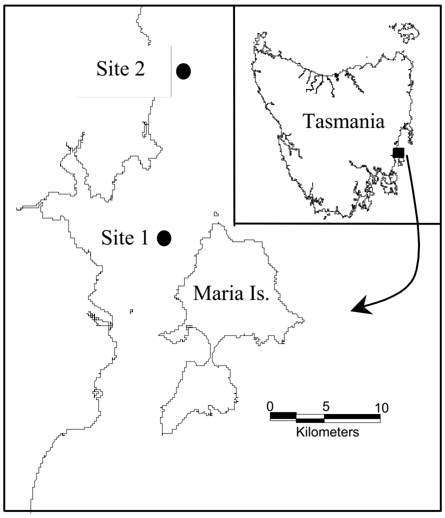

Figure 49. Site of long-line collector trials near Maria Island on Tasmania's east coast.

3) Collector servicing protocols

3a) Retention of pueruli during collector hauling

Handling and hauling techniques may affect yield from puerulus collectors. If the process of hauling a longline of collectors through the water column involves considerable vibration or rapid movement, pueruli may escape. To reduce this loss in puerulus settlement monitoring research, divers routinely bag crevice collectors prior to hauling. As collectors are hauled from the water to the boat, water washing from them may dislodge pueruli. If the latter is the case, using a dip net to lift collectors clear of the water may reduce escapement. Changes in collector design may be necessary if significant numbers of pueruli are escaping during hauling.

Twenty four Mills collectors were deployed at the site described in Experiment 1. Collectors were deployed 3 months prior to first servicing to allow conditioning. Catches from the first month were excluded from analysis, as they represent settlement during the 3 months of conditioning. Collectors were bagged at the sea floor, at the surface or left unbagged to allow us to observe if and when most loss occurs. Bags were constructed from 3 mm knotless nylon mesh, and were made considerably larger than collectors to minimise disturbance during bagging. Bags were placed around collectors by divers, and closed with a drawstring prior to hauling.

3b) Service interval

Understanding behaviour of pueruli once settled on collectors could have a dramatic effect on yield. If a collector design catches and retains pueruli well, servicing at greater intervals will lead to cost savings over more regular collection. However, if pueruli move out of collectors soon after settling, it will be important to service collectors often, centred on periods of maximum settlement.

To this end 40 Mills collectors were deployed and conditioned on the site described in experiment 1. Ten collectors were serviced daily for 14 days and 10 weekly for 1 month. Two further sets of 10 collectors allowed for 3 overlapping fortnightly samples within the same month. Collectors were bagged at the seafloor as described in experiment 3a to ensure that all settling pueruli were captured, and thereby maximise power of comparisons.

Table 31. Experimental design for sampling period trial . Each box represents the period of collection for each sample. The width of the table represents 28 days. Letters (A, B, C and D) represent groups of 10 collectors sampled on each occasion. Group D was sampled on a single occasion only, providing an overlap of fortnightly samples and allowing direct comparison of catches.

<table>
<tr><td colspan="7"></td><td colspan="14">Fortnightly (D)</td><td colspan="7"></td></tr>
<tr><td colspan="14">Fortnightly (C)</td><td colspan="14">Fortnightly (C)</td></tr>
<tr><td colspan="7">Weekly (B)</td><td colspan="7">Weekly (B)</td><td colspan="7">Weekly (B)</td><td colspan="7">Weekly (B)</td></tr>
<tr><td>A</td><td>A</td><td>A</td><td>A</td><td>A</td><td>A</td><td>A</td><td>A</td><td>A</td><td>A</td><td>A</td><td>A</td><td>A</td><td>A</td><td colspan="14">← Daily</td></tr>
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← 28 days →

2.3 Statistical analyses

Data from design trials and bagging trials were analysed by 2-way ANOVA, with month and treatment type as fixed factors. In both instances, log transformation was necessary to accommodate assumptions of ANOVA. A type III sums of squares model was used to accommodate imbalance caused by the loss of 3 Mills collectors and 2 sandwich collectors during the design trial. Significance level for the bagging trial was taken as $p = 0.1$. Trends that were clearly apparent in the data, which would have a distinct impact on commercial collection operations were significant at this level.

2.4 Results

1) Collector design trial

Tasmania's east coast experienced unusual weather patterns from winter 2000 through to summer 2000/2001. Water temperature was warmer than usual, and the NE winds that are a feature of the warmer months were infrequent. Puerulus settlement in Waubs Bay was lower over this period than for the same months in any other year since collections began in 1991.

While initially the trial was planned to run for 4 months over the winter settlement peak, it was extended in the hope that settlement would improve in summer. As both peaks were unusually weak, catch rates were low and variability high (Fig. 50). Warmer water and an absence of NE swells promoted the growth of a filamentous brown alga on collectors, becoming extremely dense in January and February 2001 and appearing to 'choke' collectors. Growth on sandwich collectors was particularly dense, and this is reflected in catch rates. Heterogeneity of variances was extreme in February. As this weed growth is not a regular phenomenon, and is unlikely to be encountered by commercial operators, catches from these months have been excluded from statistical analysis.

Tests for month and collector type are highly significant (Table 32). A post-hoc Student-Newman-Keuls test ($\alpha = 0.05$) shows catches from sandwich collectors are significantly higher than from other collectors. No other paired comparisons were significant.

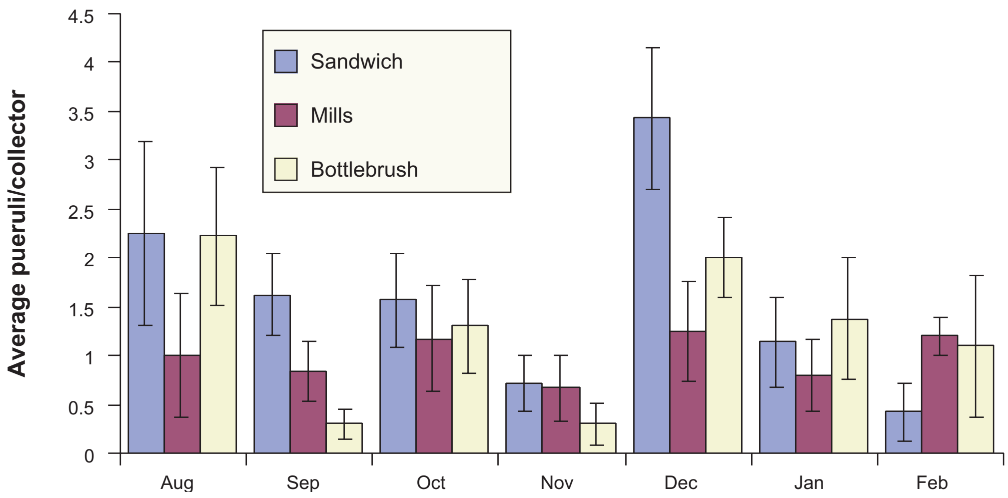

Figure 50. Average number of pueruli of *Jasus edwardsii* per collector (± SE) for sandwich, Mills and bottlebrush collectors.

Table 32. 2-Way ANOVA for collector design trials with collector type and month as fixed factors.

Source	MS	DF	*f*	Prob.
Collector type	1.099	2	3.961	.022
Month	1.544	4	5.567	<.001
Collector type * month	.306	8	1.101	.369
Error	.277	96		

Total yield from the sandwich collectors was 30% greater than from bottlebrush collectors, and 58% greater than from Mills collectors (Fig. 51). As of December, prior to the growth of the fouling brown algae, yield from sandwich collectors was 57% and 89% greater than from bottlebrush and Mills collectors respectively.

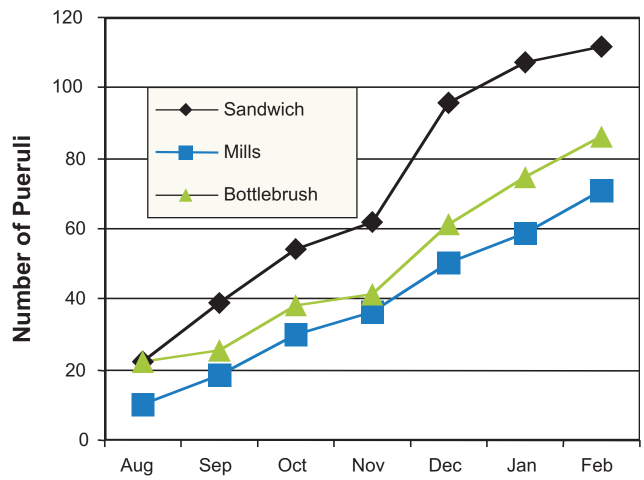

Figure 51. Cumulative yield of *Jasus edwardsii* pueruli 3 collector designs over the 7 month trial.

While not a focus of this study, a difference in the time required for conditioning was highlighted when collectors were cleared in July after 3 months conditioning. Catch from sandwich collectors was significantly higher ($p<0.001$) than from other designs (Fig. 52). A high proportion of pueruli from sandwich collectors were stage 3 and post pueruli. This suggests that sandwich collectors condition more rapidly than the other designs, and were catching efficiently during the first 3 months. The presence of large numbers of late stage pueruli showed that a high proportion of pueruli that settled early in this period were retained within the collector.

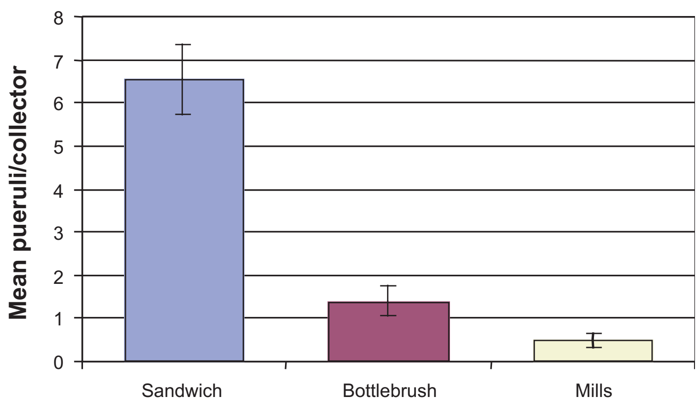

Figure 52. Mean catch (± SE) of *Jasus edwardsii* pueruli from the 3 collector types from the first collection after 3 months of conditioning.

2) Long line trial

To allow for conditioning prior to the anticipated winter recruitment peak in August/September, the longline was deployed at site 1 (Fig. 49) in May 1999. However, the 'winter' peak in this year was unusually late, not occurring until October. The line was serviced in August, October and December, yielding 6 pueruli. Catches at regular monitoring sites at Bicheno from October to January averaged 7.8 (±1.5) pueruli per collector.

In January 2000 the longline was moved to site 2 (Fig. 49). It was considered that the proximity of site 1 to the top of Maria Island might have caused a circulation anomaly, resulting in low settlement rates. The line was serviced in March and August, yielding 1 and 2 pueruli respectively.

No useful puerulus collection data were obtained from this trial, however it clearly demonstrates that a midwater longline is unlikely to be a productive way of capturing pueruli.

3) Collector servicing protocols

3a) Retention of pueruli during collector hauling

Collectors were serviced monthly from October 1999 until January 2000, corresponding with a period of strong settlement. A north-easterly gale in mid-January damaged several collectors, and 4 were lost from the site. Eight collectors had mesh missing or partially outside the external cage mesh or were tangled with other collectors. Design of clips holding the collector cages shut were modified following this event. The reduction in degrees of freedom associated with the loss of these collectors substantially reduced the power of comparisons, and data from January were excluded from analysis.

Data for the 3 treatments pooled across months (Fig. 54) suggest some pueruli are lost during hauling and some are lost as collectors break the surface. After variability due to monthly differences in settlement is included in a 2-way ANOVA, there is a significant difference between treatment ($p = 0.077$, $R^2 = 0.262$), due to higher catch rates in sea floor bagged collectors. A highly significant interaction ($p = 0.014$) is due mainly to low catches from sea floor bagged collectors in December (Fig. 54). Catch rates have been influenced by factors other than bagging, which cannot be identified with the current experimental design, but may include diver efficiency when bagging collectors or handling of unbagged collectors by the boat crew.

3b) Service interval

This trial was conducted in August 1999, and while recruitment was strong in this year, the 'winter' peak did not occur until October. Recruitment during the period of the trial was low, and daily collections were interrupted by poor weather. Only 7 of the 14 planned daily collections were possible within the allocated period, yielding 9 pueruli. Low power for treatment comparisons, and low numbers of animals in general (Fig.55) meant that planned comparisons of service intervals and puerulus development were not possible.

Comparing catches from overlapping weekly and fortnightly samples shows that pueruli are moving out of collectors over time (Fig. 56). In all cases, more pueruli were taken from collectors serviced weekly, although the relationship is non-significant due to high catches in the third fortnight (paired T-test, $p = 0.15$).

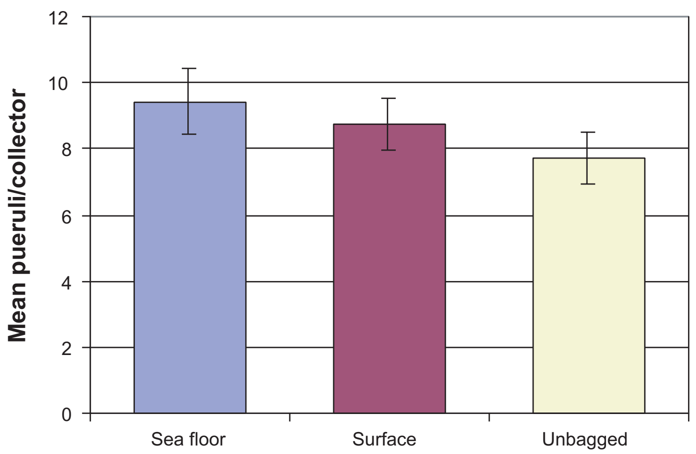

Figure 53. Mean number of pueruli of *Jasus edwardsii* per collector (± SE) for collectors bagged on the sea floor, at the surface and unbagged pooled across months.

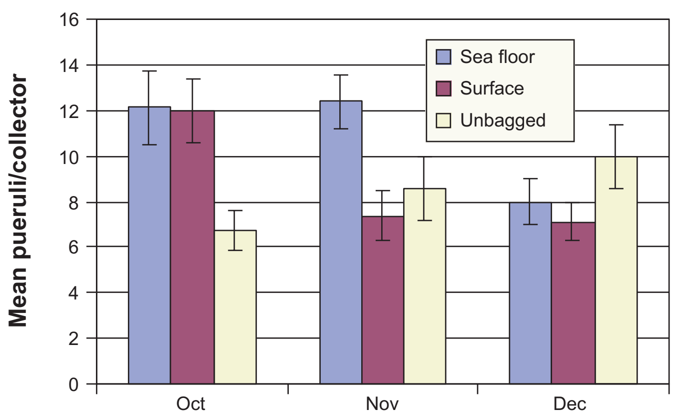

Figure 54. Monthly mean catchs of *Jasus edwardsii* pueruli (± SE) from Mills collectors bagged at the sea floor, at the surface prior to hauling from the water, and unbagged.

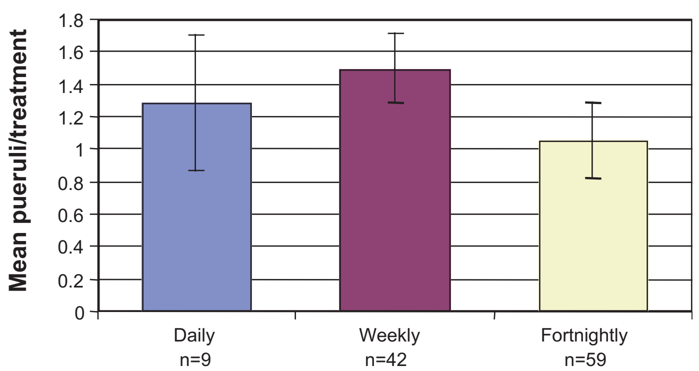

Figure 55. Mean daily catch (± SE) of pueruli of *Jasus edwardsii* per treatment (10 collectors).

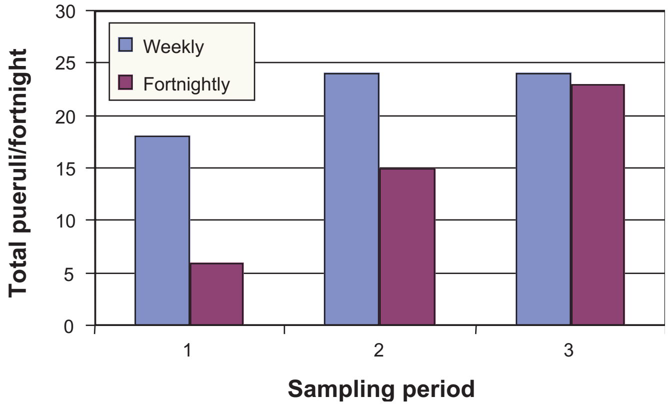

Figure 56. Paired comparisons of the 3 overlapping weekly and fortnightly catches of pueruli of *Jasus edwardsii*.

A breakdown of stages caught at different servicing intervals (Fig. 57) provides insight into puerulus development rates on collectors. If the duration of various puerulus stages can be defined, it is possible to back-calculate settlement dates from monthly puerulus catches. Knowing settlement dates will aid in correlating settlement events with environmental variables.

Unsurprisingly, collectors serviced daily caught predominantly stage 1 pueruli. The two stage 3 pueruli caught were both from the first daily sample, and it is possible that they were not cleared from collectors following the conditioning period. A high percentage of pueruli have entered stages 2 and 3 in weekly collections. In fortnightly collections, a higher percentage still are at stage 3. Few animals had moulted to post pueruli in fortnightly samples, and the few that had may have remained in collectors from the conditioning period. These results suggest stage 2 occurs within a week settling, stage 3 within 1 to 2 weeks and the post puerulus stage at greater than 2 weeks. Development rates are likely to vary with water temperature.

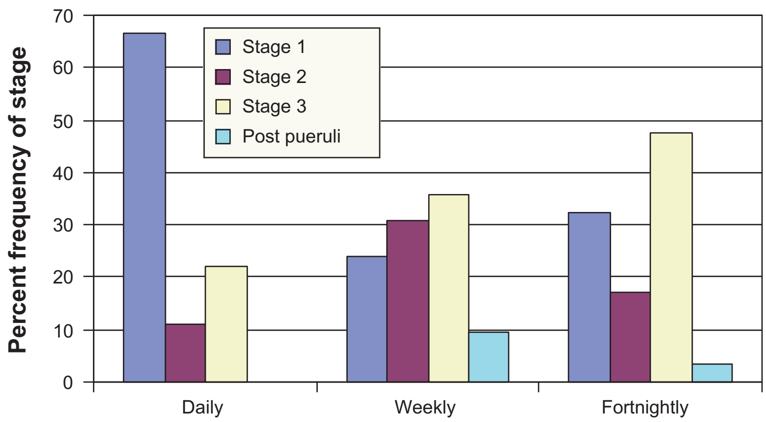

Figure 57. Percent frequency of puerulus stages of *Jasus edwardsii* in daily, weekly and fortnightly catches.

2.5 Discussion

Problems experienced in collector trials are indicative of those likely to face commercial operators. High temporal variability in settlement requires collectors to be in the water for long periods to increase the chance of coinciding with seasonal peaks. However, areas allocated for collection in Tasmania are characterised by exposed coast, and the longer gear is in the water, the more susceptible it is to damage from wave action. It is apparent that rigging equipment used in some trials was not adequate to withstand extreme weather events.

For powerful statistical analysis of trends in settlement, scientific collectors must catch high numbers of pueruli with minimal variance between collectors. The foremost criterion for the selection of commercial collectors is minimising cost per puerulus retained. Factors affecting this include catch rates, cost of collector construction and associated rigging, durability of collectors and rigging, and costs associated with servicing.

It appears that the use of 'seaweed' type collectors such as sandwich collectors for monitoring of *J. edwardsii* settlement was previously discounted based on incomplete information. Early trials in southern Australia (Kennedy *et al.* 1991) did not include this type of collector deployed on the sea floor, but only at the surface as done for *P. cygnus* (Phillips 1972). Trials in New Zealand (Booth 1979) showed tassel collectors caught at least as well as crevice collectors when moored near the sea floor, however , crevice collectors were favoured because they were cheaper to build and more robust. While no direct comparisons were made in this study, data from this and a previous trial (Mills *et al.* 2000) suggest that sandwich collectors would catch significantly more *J. edwardsii* pueruli than crevice collectors if deployed on the sea floor. While this may relate purely to the relative size of sandwich and crevice collectors used in these trials, it differs considerably from the results of Kennedy *et al.* (1991).

Standardising catch rates of different collector types for the purpose of scientific trials is difficult, and to the authors knowledge has not been addressed in the literature. While size of collectors of the same design has a linear effect on catch rates (see Chapter 3), even this comparison is difficult between collector types. Different measures of size such as surface area of the collector, total surface area of settlement substratum or volume would give vastly differing results. For commercial trials, standardisation should be by cost. In this case, while catch from sandwich collectors was higher than that from other collector designs (Fig 58A), once cost is considered this design is not appropriate for commercial collection (Fig 58B).

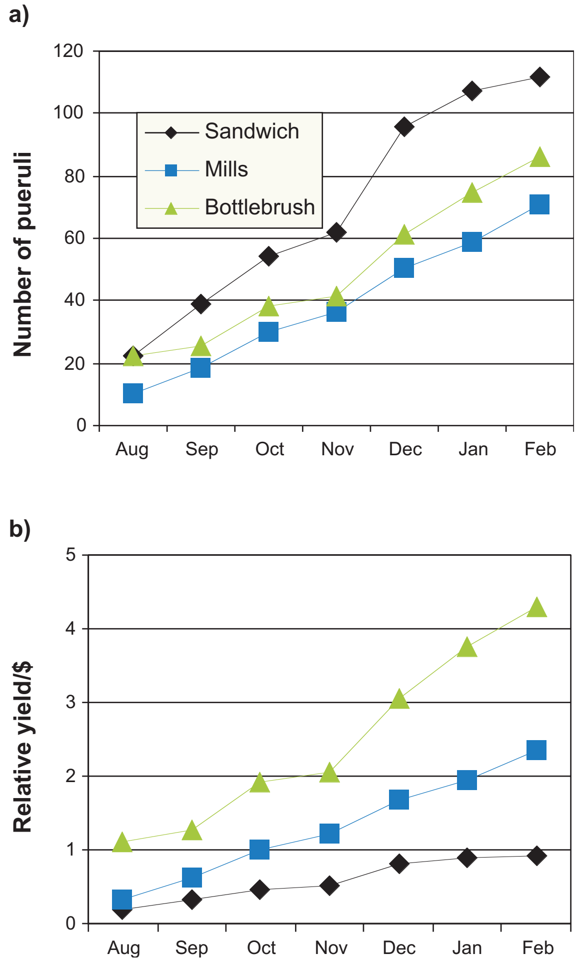

Figure 58. **a)** Cumulative yield of *Jasus edwardsii* pueruli from 3 collector designs over the 7 month trial and **b)** relative yield from each collector design adjusted for the cost of constructing the collectors.

While this standardisation is crude in that it only takes into account cost of collector construction, other factors are likely to increase relative costs of using sandwich collectors. Resistance to swell action is highest for sandwich collectors, requiring heavier and more expensive rigging. Sandwich collectors are heavy to lift from the water and slow to service compared with other designs.

While sandwich collectors in their current form are not a viable option for commercial collection of *J. edwardsii*, they show some desirable traits. Tasmanian permit conditions require collectors to be serviced at least monthly once deployed. If collectors require 3 or more months to condition, monthly servicing over this period is wasted effort. Collectors that catch well immediately following deployment will offer a considerable cost benefit. Wear on collectors and rigging and the probability of encountering extreme weather events will also be reduced.

A high proportion of the cost of sandwich collectors is the time consuming construction and the PVC sheets and frame required to hold the tassels. Cost of tassels is in the order of $30 per collector, on a par with the cost of constructing the other designs in this trial. Investigation of cheaper ways of presenting this substratum type is warranted. Collectors used in Japan have a courser tassel material and a plastic mesh backbone (Fig. 59). A similar backbone would substantially reduce the cost of sandwich collectors.

Figure 59. Collector used for catching *Panulirus japonicus* pueruli in Japan.

Extremely low catch rates from the midwater longline were unexpected. The method and location used were the same as for scallop spat collectors that caught good numbers of pueruli in previous years. However, the low catch concurs with a previous study of depth distribution of *J. edwardsii* puerulus settlement (Booth *et al.* 1991). Most pueruli were caught near shore in shallow water (<12 m), with collectors deployed at the sea floor. Similarly, *P. cygnus* only settles on collectors placed near the shore (Chapter 3, this report). Unfortunately, servicing of scallop spat bags did not coincide with our trial so direct comparisons of catch rates could not be made. Given that mesh collectors are known to catch pueruli well, it seems likely that settlement in this area was low during the trial. Previous collections from this area may have been made in exceptional years, and inshore collectors in this area may have caught higher numbers.

The primary response of settled pueruli to disturbance is to hold on to the substratum, resulting in the loss of relatively few pueruli during hauling. Enclosing collectors on the sea floor in the trial lead to an approximately 20% increase in catch over collectors netted at the surface. The added complication and expense involved in bagging, and the increased likelihood of entanglement of complicated equipment would not appear to warrant development of remote bagging techniques. The relatively simple and cheap option of lifting collectors from the sea surface using a scoop net may prove worthwhile, as total yield was increased by about 15% over unbagged collectors in the trial.

It appears that considerable numbers of pueruli emigrate from collectors over periods of days to weeks (see also results in Chapter 3). The implications for commercial harvesting is that yield from collectors will be maximised by servicing at intervals of one week or less during peak settlement periods. To achieve this, an inexpensive method of detecting settlement peaks is required. Once sites with relatively consistent settlement rates have been identified, a small number of collectors serviced at weekly intervals could be used to detect periods of high settlement. Once numbers on these collectors increase, all collectors can be serviced on a weekly basis until catch rates decline.

Based on this research, advice given to commercial operators has been to deploy a large number of cheap collectors such as bottlebrush collectors, set close to the sea floor in shallow water. Further investigation of the use of tassel substratum as used in sandwich collectors has been suggested. Some operators have indicated they will be building bottlebrush collectors with alternate layers of mesh and tassels.

A summary of work conducted can be found at the T.A.F.I. website below.

http://www.utas.edu.au/docs/tafi/TAFI_Download.htm#Lobster%20puerulus%20collection%20information

3. CHAPTER 3
To establish techniques for large scale harvesting of pueruli for rock lobsters

3.1 Introduction

The high dollar value of rock lobsters has made them an interesting prospect for aquaculture and has stimulated numerous reviews (e.g., van Olst *et al*. 1980; Provenzano 1985; Kittaka and Booth 2000). A major stumbling block in realizing the aquaculture potential of these animals has been the difficulties of rearing the larvae through their long and complicated pelagic stages. Although some species have been successfully reared through their larval life (Kittaka 2000), the production of large numbers of postlarvae has not yet been possible, and successful commercial application seems some years away.

In contrast, the postlarvae are relatively easy to rear, and numerous authors have reported on the potential for their on-growing to marketable size (e.g., Tholasilingam and Rangarajan 1986; Phillips 1988 1997; Meagher 1994; Kittaka and Booth 2000). Good markets, particularly in Japan, exist for small lobsters, and it is this market that would initially be the target of those contemplating the harvesting and culturing of spiny lobster pueruli.

A number of different types of collectors have been used to catch settling pueruli (see review by Phillips and Booth 1994), but none was designed to catch large numbers. Research is needed to estimate the likely impact of large scale harvesting of puerulus on the wild fishery and to establish methods and equipment necessary to catch large quantities of pueruli in the most cost effective way. This chapter reports initial studies developed to catch large numbers of pueruli for aquaculture or enhancement purposes.

3.2 Materials and methods

3.2.1 Onshore/offshore trials

Optimal depths and distances offshore for the collection of pueruli were tested during 1998 with tassel-style collectors based on the 'seaweed' collector (Montgomery and Craig 1994), described more fully below as 'sandwich' collectors

Sandwich collectors (each providing a total collection area of 0.43 m^{2}) were attached in tandem to dropper ropes at various depth intervals along an offshore transect west of Cervantes, Western Australia (Fig. 60), over two lunar months during October and November 1998. The collectors were initially positioned in waters approximately 3, 10, 36–40, 60, and 120 m deep. After one month the collectors set at 10 m had to be repositioned to 20 m because of gear damage caused by surge and swell associated with the shallows. The inshore station (near Cervantes) was approximately half a nautical mile from the beach, and that farthest offshore was approximately 17 nautical miles west of that point (Fig. 61).

Lines of collectors were set according to the bottom type and depth profile. The two inshore lines were over hard bottom, but those in the deeper water were over hard reef (36 m), sand/weed (40 m), hard bottom at the top of the drop-off (50 m), and finally silt on the drop-off slope (~120 m). Because of concerns about the buoyancy of the floats and the ability of the anchors to prevent the dropper lines from drifting, each line was limited to supporting a maximum of four sandwich collectors. The four inshore lines were made up of two dropper lines, one with a surface and a bottom collector and the other with a surface and a mid-water collector set at 20 m (Fig. 60). The most inshore station had only two collectors, one at the surface and the other at the bottom (Fig. 60). The station farthest offshore was made up of four dropper lines, two with surface collectors and one with collectors at the bottom (Fig. 60).

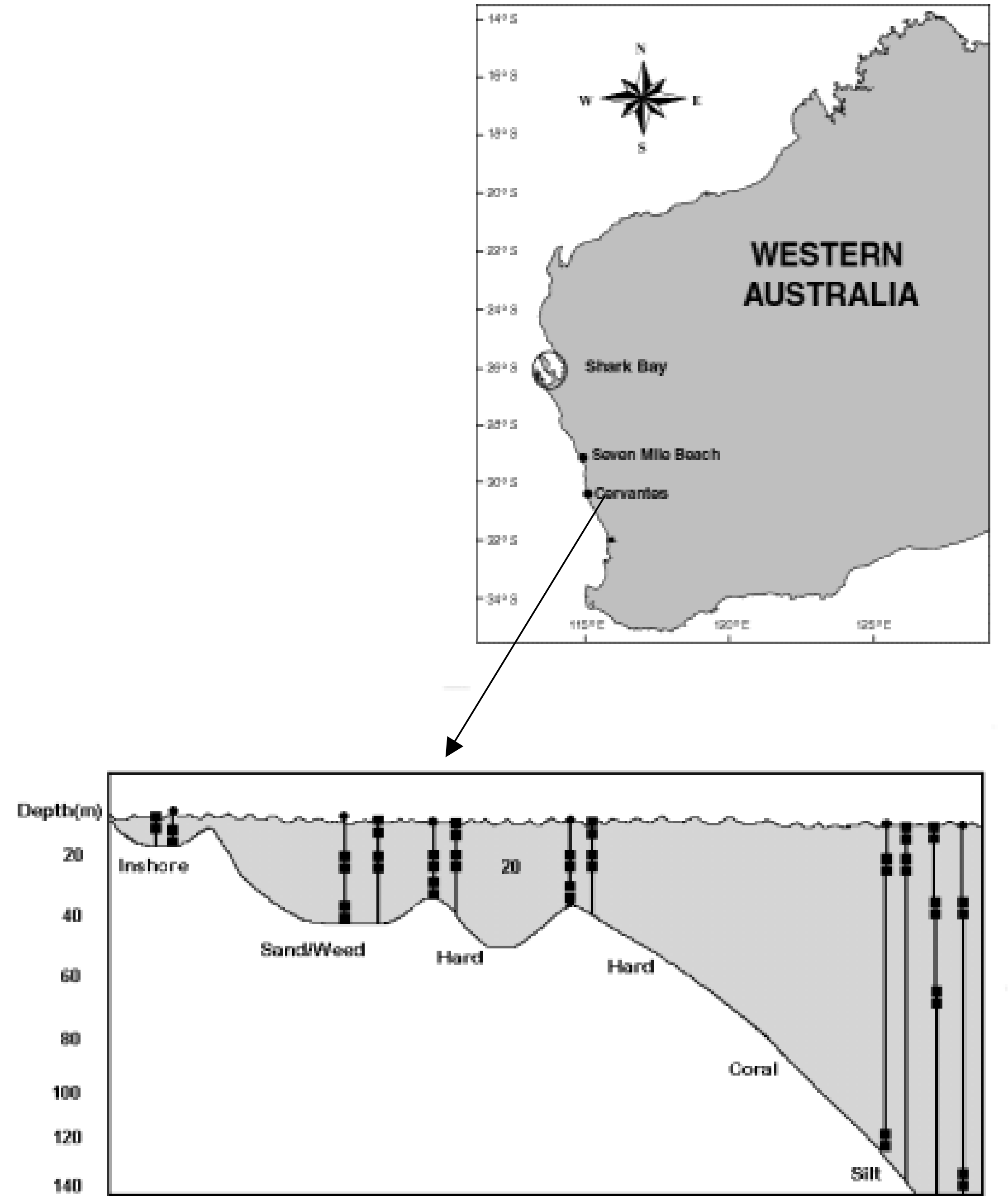

Figure 60. Map showing locations of puerulus sampling in Western Australia and diagrammatic transect across the shelf west of Cervantes, showing the locations of dropper lines and their associated collectors.

Those lines had mid-water collectors at 20, 40, and 60 m. Using the above arrangement, inshore-offshore puerulus settlement rates were measured on four daily intervals throughout the water column over two lunar months. The position of deployment is given in Table 33.

Our sampling was conducted on a chartered commercial rock lobster vessel. The gear was hauled first by grappling the collector float line, winching it very slowly (as slow as the winch would permit) until a collector appeared alongside. At that point the collector was man-handled onboard (it requires two people to lift the net collector as they are heavy when conditioned). Both floats and the mooring bridle were removed before the collectors were serviced.

The spinning shaft was then slid into the central holes in the Jarrah wood braces. The whole unit was then placed inside a large tub (see Figure 62) over which a plastic cover is placed and the sandwich was rotated both clockwise and counter-clockwise 20 times. For large-scale operations a device with an electric motor fitted in a similar fashion to that of a chicken rotisserie would speed up the process of sampling. The sample obtained was then poured into a sieve, sorted and the pueruli counted.

Table 33. Location of sampling sites near Cervantes, W.A.

Sampling Sites	Approx. Depths(m)	Positions
Inshore	2 - 6	(30° 31'S and 115° 02.5'E)
Offshore	0 - 20	Lines 1&2 (30° 32.61'S and 115° 01.38'E)(30° 32.52'S and 115° 01.34'E)
	0 - 40	Lines 3&4 (30° 33.97'S and 114°58.37'E) (30° 33.97'S and 114° 58.37 'E)
	0 - 40	Lines 5&6 (30° 34.07'S and 114° 58.41'E) (30° 34.07'S and 114° 58.41'E)
	0 - 40	Lines 7&8 (30° 36.04'S and 114° 54.07'E) (30° 36.04'S and 114° 54.07'E)
	0 - 120	Lines 9-12 (30° 36.14'S and 114° 54.11'E) (30° 36.14'S and 114° 54.11'E) (30° 38.37'S and 114° 49.70'E) (30° 38.37'S and 114° 49.70'E)

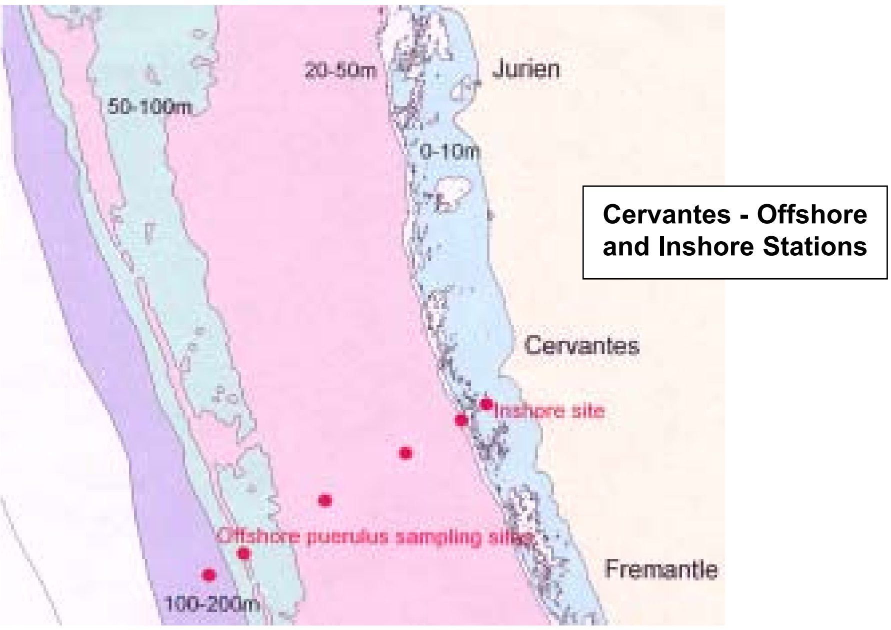

Figure 61. Map showing the bathymetry off the Cervantes region of the Western Australian Coast and the positions of the six sampling stations where collectors were set during October and November 1998.

Figure 62. Spinning tub for sampling collectors.

3.2.2 Types of Collectors

Collectors of different designs and sizes were deployed at Seven Mile Beach (near Dongara) to examine their catchabilty, ease of servicing and ability to withstand the prevailing weather conditions. Because of the large number of these collectors required to catch sufficient quantities, cost of manufacture was also an important consideration.

The various types (and numbers, in parentheses) and sizes of collector trialled were:

i) **Mills collector** (6): The design was developed by David Mills at the Tasmanian Aquaculture and Fisheries Institute for the collection of *Jasus edwardsii* pueruli. Each was constructed of a framework of plastic mesh in a square box shape approximately 40 cm x 40 cm (Fig. 63).

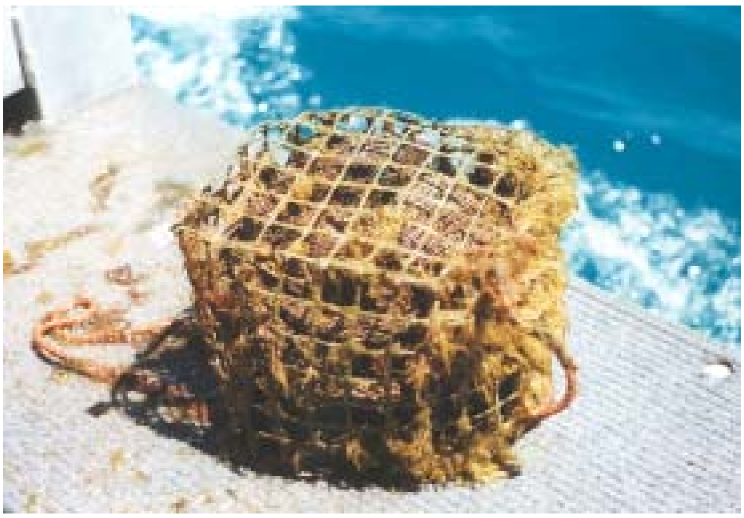

Figure 63. Mills puerulus collector.

The plastic mesh framework was filled with approximately 2 kg of used prawn trawl net.

ii) **Witham collector** (6): This type of collector was designed in Florida, USA (Whitam *et al*. 1968) to catch *Panulirus argus* pueruli. Those used in these trials were modified from the original design constructed of 30 cm ? 60 cm ? 3 cm wide floatation board made from marine-grade plywood filled with polyurethane floatation sheeting. The 'leaves' of webbing were 30 cm ? 10 cm and were of industrial-grade grey air-conditioner filter material (Fig. 64).

Figure 64. Witham puerulus collector.

iii) **Purse type collector with tubes** (9): These collectors were similar in shape to the Serfling and Ford (1975) collector used to catch *Panulirus interruptus* pueruli but were constructed of rigid plastic mesh and filled with artificial fibre, not natural seaweed (Fig. 65a).

A) **B)**

Figure 65. A) Purse type puerulus collector so different sizes. B) PVC tubes inserted into purse collectors.

The design was similar to the Mills collectors in that they were constructed of a framework of plastic mesh, but rather than being the squat shape of the Mills collectors, these had a vertical pallet-like shape (i.e. thin and flat). They were filled with old trawl net, which was attached to a rigid frame of plastic oyster mesh, which fitted inside the 'purse'. Within the purse were two PVC tubes (50 mm in diameter ? 30 cm in length) sealed at one end and filled with 12-mm black poly irrigation pipe (Fig. 66b). Three replicates of three different sizes of purse collectors (0.25 m^2, 1.0 m^2, and 1.5 m^2) were used.

iv) **Sandwich collector** (12): These collectors were a modified version of the 'sea-weed-type' collector developed by Montgomery and Craig (1994). They consisted of two sheets of grey industrial PVC, each sheet corresponding to a third of the collection area of the standard Phillips puerulus collector (615 ? 350 ? 4.5 mm) described by Phillips (1972). The bales of tassels fixed to the outer surface of each sheet were polyethylene split-fiber 125 tex manufactured by "Kinnears Pty Ltd.", Victoria, Australia.

a) b) c)

Figure 66. Sandwich puerulus collector a) side on profile, b) front on and c) spinning shaft and collector.

The two single-sided sheets (with a total area of 0.43 m^2) were secured back-to-back by bolts to a timber frame (47 mm ? 45 mm ? 38 mm) that acted as a brace Fig 66a & 66b. The braces allowed both for the attachment at the top for floats and for a shaft to slide through a central hole and secure the sheets when they were checked by being spun centrifugally (Fig. 66c). Three replicates of four different sizes of sandwich collectors (0.11 m^2, 0.22 m^2, 0.43 m^2, and 0.86 m^2) were used.

v) **Rossbach collector** (6): Named after one of the authors (M.R.), these collectors consisted of polyethylene split-fiber tassels (Kinnears Pty Ltd., Victoria, Australia) attached at 40-mm intervals along a 2-m length of a rope (Fig. 67). The rope was suspended either vertically or horizontally in the water.

Figure 67. Rossbach horizontal type puerulus collector.

3.2.3 Experimental array design

Analysis of previous data

Monthly catches of *Panulirus cygnus* pueruli from Phillips collectors set between August 1971 and February 1972 at Seven Mile Beach (Phillips and Hall 1978), were used to examine the relationships between neighbouring collectors before the experiment described here was set up. The original data were composed of catches of pueruli on a set of eight collectors arrayed in a square, each collector set approximately 2 m from its nearest neighbour.

An ANOVA conducted on these data treated them as a split-plot design. As expected, settlement rates differed significantly from month to month ($P < 0.001$). More importantly, however, unlike the earlier analysis of these data (Phillips and Hall 1978), ours found marginal interactions between catch rates of corner collectors ($P = 0.078$) and those of collectors on opposite sides of the square (i.e., layer effects) ($P = 0.079$). The collector in the middle of the first row caught the most pueruli, presumably because of neighbour effects. Because the eight collectors were relatively close to each other, we have conservatively suggested that 10% (or even higher) be used as the level of high statistical significance and 20% the level of marginal significance. With these levels of significance, neighbour carry-over effects (Cheng 1996; Cheng and Street 1997) were marginally significant ($P = 0.16$) and square-of-time effects highly significant ($P = 0.04$). Clearly, therefore, these effects must be considered when new experiments are designed to test type or size of collector for puerulus harvesting.

We distinguish between neighbour effects, those that arise simply from collector proximity, and carry-over effects, the influence of directional effects on collector catch rates (Fig. 68). Because pueruli swim inshore, collectors in columns on the seaward side of the array are more likely to catch pueruli than those on the shoreward side. Carry-over effects are therefore a measure of the possible positive influence of outer collectors on catch by neighbouring collectors in the same columns (Fig. 62). Square-of-time effects refer to the nonlinear month-to-month catch relationship that is evident in this and other studies (eg. Phillips and Hall 1978).

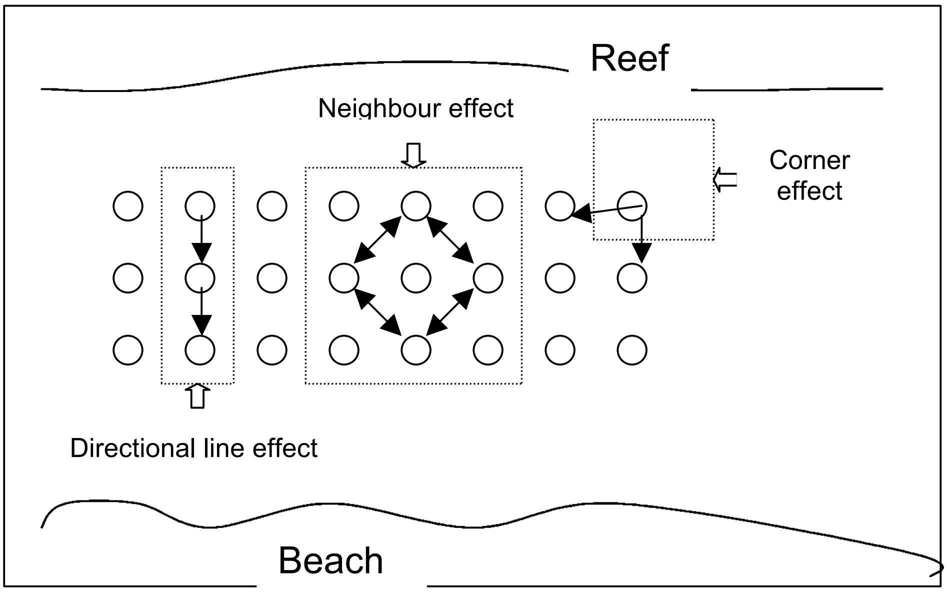

Figure 68. Diagrammatic representation showing corner, directional line and neighbour effects in an array to test collector types.

3.2.4 Experimental design of gear trials

In an experiment designed to compare different collector types conducted at Seven Mile Beach (Fig. 69) during 1999–00, collectors were set out in three rows and each collector type in two or more columns (Fig. 70). Collectors were spaced 5 m apart. This distance was chosen as the minimum distance likely to prevent tangling during servicing of the gear.

On the basis of the revised analysis of the Phillips and Hall (1978) study, in which the collectors were spaced 2 m apart, we assumed that the collector array spacing in our experiment was likely to produce directional and carry-over effects, and the design was devised to take these possibilities into account. In taking these into account, we assumed (i) that different areas along the extent of the lines of collectors were likely to have different catch rates, but within each set (column) of collectors and within localized areas along the line, conditions were homogenous, (ii) that there were corner and marginal effects, (iii) that there were carry-over effects along each vertical line from the ocean, and (iv) that neighbour effects would result from the attraction of neighbouring collectors.

Two experiments were run concurrently. The first was designed to determine which collector type (of the five tested) would produce the highest puerulus catch rate. The second examined the relationship between the size (surface area) of the collector and resulting puerulus catch rates. In the second experiment, puerulus catch rates were compared for 12 sandwich collectors (three each of four different sizes) and nine purse collectors (three each of three different sizes). All collectors used in these experiments were put in the ocean in the same area for conditioning for one month.

3.2.4.1 Effects of collector designs and size on catch rates

Three lines of 11 different collector types and/or sizes were deployed at Seven Mile Beach in July 1999 (Fig. 71). Seven Mile Beach was selected as the main study site because it had a previous history of research there and offered protection against the winter blows. The gear was allowed to condition for one month before the experiment began. The experimental design of the gear consisted of three lines running parallel to the coast (i.e., approximately north to south) in depths of 2 to 3 m.

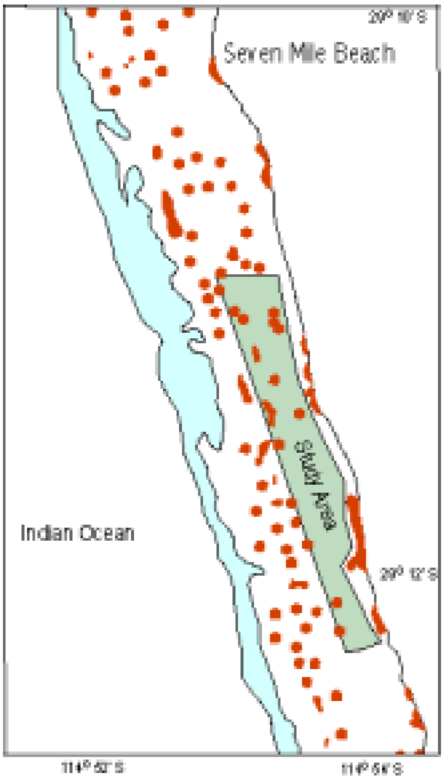

Figure 69. Shows study area at Seven Mile Beach (near Dongara),Western Australia.

NOVEMBER

Ocean

	1	2	3	4	5	6	7	8	9	10
Line 1	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3
Line 2	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3
Line 3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3

Beach

DECEMBER

Ocean

	1	2	3	4	5	6	7	8	9	10
Line 1	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3
Line 2	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3
Line 3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3

Beach

JANUARY

Ocean

	1	2	3	4	5	6	7	8	9	10
Line 1	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3
Line 2	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3
Line 3	D3	D3	D3	D3	D3	D3	D3	D3	D3	D3

Beach

Figure 70. Design of the experiment used to test frequency of collector servicing on pueruli catch rates at Seven Mile Beach. Those collectors identified by grey hatching in the above experimental design, were sampled daily for seven days over the new moon period and all others were sampled monthly at the time of full moon.

First Month (August) and Second month (September)

Ocean

B	A	D1	D2	D3	D4	C3	C2	C1	E2	E1	B	A
B	A	D1	D2	D3	D4	C3	C2	C1	E2	E1	B	A
B	A	D2	D3	D4	D1	C2	C1	C3	E1	E2	B	A

Shore

Third month (October)

Ocean

D4	D3	D2	D1	A	A	B	B	C1	C2	C3	E1	E2
D4	D3	D2	D1	A	A	B	B	C1	C2	C3	E1	E2
D1	D4	D3	D2	A	A	B	B	C3	C1	C2	E2	E1

Shore

Fourth Month (November)

Ocean

C1	C2	C3	B	B	E1	E2	A	A	D4	D3	D2	D1
C1	C2	C3	B	B	E1	E2	A	A	D4	D3	D2	D1
C3	C1	C2	B	B	E2	E1	A	A	D1	D4	D3	D2

Shore

Fifth Month (December)

Ocean

A	A	C1	C2	C3	D4	D3	D2	D1	E1	E2	B	B
A	A	C1	C2	C3	D4	D3	D2	D1	E1	E2	B	B
A	A	C3	C1	C2	D1	D4	D3	D2	E2	E1	B	B

Shore

Figure 71. Position of pueruli collectors in the experiment at Seven Mile Beach, to assess the effect of collector type and size on pueruli catch rate. Where A= Mills; B1=Witham; Sandwich type, C1 ($0.25m^2$), C2 ($1.0m^2$), C3 ($1.5m^2$); Purse type, D1 ($0.11\ m^2$), D2 ($0.22\ m^2$), D3 ($0.43\ m^2$) D4 ($0.86\ m^2$); Rossbach, E1 (vertical) and E2 (horizontal).

3.2.4.2 Minimum sample sizes for testing collector types and sizes

Statistical power is the power to avoid Type II error (failure to reject a false null hypothesis; Cohen 1988). The power of the test is a function of (Searcy-Bernal 1994)

1) α, level of significance;
2) $\boldsymbol{k}$, number of treatments;
3) $\boldsymbol{n}$, number of replicates;
4) σ, the common population standard deviation; and
5) μ, the common population mean,

where

$$\boldsymbol{d} = \frac{\delta}{\sigma} = \frac{\mu_{\max} - \mu_{\min}}{\sigma} \qquad (1)$$

is the ratio of the difference between the maximum and the minimum population means to the standard deviation, and the abstract index is

$$\boldsymbol{f} = \boldsymbol{d}\sqrt{\frac{1}{2\boldsymbol{k}}}\ . \qquad (2)$$

In the experiment that tested differences between collector types, a power of at least 0.8, $\alpha = 0.05$, $\boldsymbol{k} = 5$, and minimum $\boldsymbol{f} = 0.4$, in the absence of prior knowledge of $\boldsymbol{d}$, was considered necessary to determine $\boldsymbol{n}$. From the table in Searcy-Bernal (1994), the minimum number of replicates needed was 16. In the absence of prior information on $\boldsymbol{d}$, it is likely that the minimum number of replicates needed would be 16.

In this case the data from August 1971 to January 1972 has been used as prior knowledge to determine $\boldsymbol{d}$:

$\boldsymbol{u}_{max} = 12$, $\boldsymbol{u}_{min} = 3.75$, and $\sigma = 4.01$. Therefore $\boldsymbol{d} = 2.06$ and $\boldsymbol{f} \approx 0.7$ from equations (1) and (2). From the table in Searcy-Bernal (1994), the minimum number of replicates needed for testing five types of puerulus collectors is 6 replicates for each month of sampling. This calculation demonstrates that prior information can help to conserve experimental resources.

For the second experiment examining the relationship between puerulus collector area and catch rates, we had no prior knowledge of $\boldsymbol{d}$. Based on the information at the beginning of this section, 16 replicates are needed. We believed, however, that the standard deviation in the second experiment would be much smaller than that in the first, because most of the collectors were smaller than the standard collector. In fact, Table 1 shows that the standard error of 0.43-m^2 sandwich collectors is higher than the standard error of the other collectors. If $\sigma = 0.25(\mu_{max} - \mu_{min})$, $\boldsymbol{d}$ can be determined to be 4. Therefore $\boldsymbol{f} \approx 1.4$, and the number of replicates required for testing this relationship between 3 or 4 collector types is 3.

The five collector designs were tested over the six peak puerulus settlement months between August 1999 and January 2000 at Seven Mile Beach. The experimental design used each month is shown in Fig. 71.

The design of the experiment remained unchanged in the first and second months but was rearranged in subsequent months. We randomized the five collector types by column, not by row, to avoid the introduction of errors due to carry-over and neighbour effects. Particular types of collectors were restricted to particular columns within the experimental design, but different-sized collectors of the same design were not restricted in this way.

3.2.4.3 Effect of servicing frequency on catch rates

We conducted an experiment to determine whether the frequency of collector servicing would increase or decrease catch rates.

Approximately half of the sandwich collectors in a separate array of 30 collectors, adjacent to the experiment testing collector types, were serviced daily for seven days over the new moon in November and December 1999 and January 2000; the remainder were serviced only once at the full moon over this same period (Fig. 70). The collectors used in this service-frequency experiment were put into the ocean in the same configuration shown in Fig. 70 for two months to condition before the experiment began.

At the beginning of the experiment, an ANOVA was used to test whether catch rates of the collectors were homogenous within each line. The effect of treatment ($P > 0.99$) was not significant during the conditioning period, so catch rates of the collectors were homogenous within each line at the beginning of the experiment. The effects of line (*P* = 0.17) and month (*P* = 0.14) were not significant or only marginally significant (<0.2) because we conducted insufficient observations. We considered it important to incorporate these potential effects into the experimental design, despite the low significance, because the analysis lacked power as a result of low sample size.

The total numbers of pueruli caught by each collector over a month were compared with an analysis of variance (ANOVA) to determine whether the frequency of servicing resulted in significant differences in catch rates.

3.3 Results

3.3.1 Onshore/offshore trials

Even though collectors were set for two months over what is normally the main period of puerulus settlement (Phillips 1972), the only settlement recorded was on gear set in the inshore area (depths <5 m), where 13 pueruli were caught over the two lunar months of sampling, all by the surface collectors (Fig 72).

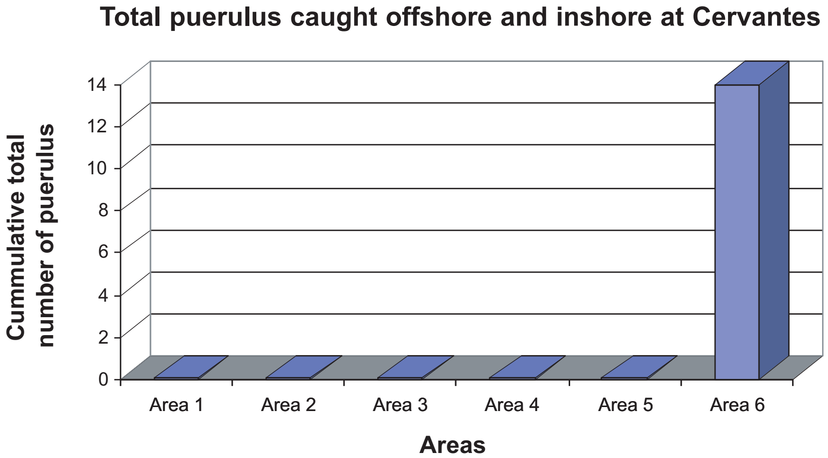

Figure 72. Puerulus catches of *Panulirus cygnus* at Inshore to Offshore Stations off Cervantes,W.A.

3.3.2 Comparisons of collector designs

Mean monthly catch rates for the five different collector types over the duration of the experiment are shown in Table 34 . In order to compare the performance of different types of collectors, we evaluated only those of similar size. The effect of treatment (collector type) was significant (*P* < 0.001); sandwich collectors had the highest catch rates (Table 35), followed in order of puerulus catch by Mills, Purse, Rossbach, and Witham collectors.

Table 34. Mean catches (standard error in parentheses) of pueruli caught on different types of collectors in the lunar months August–December 1999 at Seven Mile Beach.

Type and no. of collectors		Size (m^2)	Mean (SE)					
			August	September	October	November	December	January
Mills	6		0.60 (0.40)	7.50 (2.59)	5.83 (2.50)	2.67 (0.95)	2.5 (0.76)	0.5 (0.22)
Witham	6		0.00 (0.00)	0.00 (0.00)	0.50 (0.34)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
Purse	3	0.25	1.67 (0.88)	5.00 (2.00)	8.67 (3.53)	1.67 (1.20)	2.34 (0.88)	0.67 (0.67)
Purse	3	0.5	2.50 (1.50)	4.00 (2.00)	1.67 (1.20)	2.67 (0.67)	4.00 (2.08)	0.67 (0.33)
Purse	3	1.5	1.00 (0.58)	13.00 (3.46)	13.00 (4.73)	3.67 (1.86)	4.00 (1.00)	0.33 (0.33)
Sandwich	3	0.11	0.33 (0.33)	5.00 (3.00)	2.33 (1.45)	0.33 (0.33)	1.00 (0.00)	0.00 (0.00)
Sandwich	3	0.22	1.00 (0.00)	2.00 (1.15)	1.33 (0.88)	1.67 (0.33)	0.00 (0.00)	0.00 (0.00)
Sandwich	3	0.43	8.50 (2.50)	9.33 (3.48)	7.67 (3.71)	1.33 (0.88)	0.67 (0.33)	0.00 (0.00)
Sandwich	3	0.86	13.50 (0.50)	17.67 (7.80)	19.00 (8.36)	10.00 (1.15)	6.67 (1.76)	2.00 (1.53)
Rossbach	3	Vertical	3.50 (2.50)	3.00 (2.00)	2.00 (2.00)	1.00 (0.58)	5.00 (0.58)	0.33 (0.33)
Rossbach	3	Horizontal	0.00 (0.00)	1.67 (1.67)	4.67 (1.45)	1.67 (0.33)	0.67 (0.33)	0.67 (0.33)

We assumed that each line was a distinct entity and that each column of the block was an experimental unit. An ANOVA was used to test the effects on the catch of pueruli of each line, neighbour effects on collectors in other lines, effects of time (months), effects of collector type and corner effects from the four corners, and the covariate carry-over effects from collectors in offshore to onshore lines (i.e. lines 1 to 2 and lines 2 to 3).

Table 35. Summary of mean catches (standard error in parentheses) of pueruli caught on different types of collectors in the lunar months August–December 1999.

Type		Size (m^2)	Mean (SE)		
			Overall	Sept-Oct	Other months
Mills	6		3.42 (0.75)	6.67 (1.73)	1.61(0.38)
Witham	6		0.086 (0.063)	0.25 (0.18)	0.00 (0.00)
Purse	3	0.5	2.59 (0.58)	2.83 (1.17)	2.45 (0.68)
Sandwich	3	0.43	4.35 (1.27	8.50 (2.31)	2.09 (1.05)
Rossbach	3	Vertical	2.27 (0.61)	2.50 (1.28)	2.17 (0.69)
Rossbach	3	Horizontal	1.64 (0.51)	3.17 (1.19)	0.82 (0.22)

The mean catches with standard errors for 39 sandwich collectors spread out in 3 lines (Table. 34) over the six-month period between August 1999 and January 2000 are shown in Table 35.

Catches from September and October were similar ($P > 0.2$), and catches from August, November, December, and January were similar ($P > 0.2$), so the data were divided into these two monthly groupings for further analysis. The benefit of treating the data in separate groupings is that the variance is smaller than if they are combined, and dealing with smaller variances improves the statistical power associated with the results. The mean and standard error of catch in each month are listed in Table 3. September and October catches were significantly different from those in the other four months ($P < 0.05$).

Table 36. Catch of pueruli (mean and SE) by each collector from August 1999 to January 2000.

August	September	October	November	December	January
2.19 (0.67)	5.84 (1.13)	5.61 (1.17)	2.25 (0.46)	2.21 (0.41)	0.44 (0.15)

3.3.3 Neighbour effects

Published data from the 1970s on the effect on catches of collector arrays and locations were re-examined with a general linear model. The analysis revealed marginally significant corner and layer effects, carry-over effects, and square-of-time effects. Five collector designs were therefore set in the shallows, two of which had replicates of three different sizes, and were checked over four lunar months during peak settlement. Sandwich collectors had significantly better catch rates than others ($P < 0.001$), and settlement rates were highly correlated with collector dimensions ($r = 0.72$). Daily servicing for seven days around the time of new moon, yielded catches 170% higher than those from a single monthly servicing ($P < 0.001$). Results indicate that tests for collectors must take into account corner, carry-over, neighbour, and layer effects and that to do so they must be set out in an array and repositioned after each sampling.

The analysis assumed that corner collectors had two neighbours, collectors on the outer edge of the design had three, and those inside the design had four (Fig. 71). Directional carry-over effects from offshore to inshore columns of collectors were significant ($P < 0.001$), and the estimated coefficient was 0.33. The effects of time ($P < 0.001$) and treatment ($P < 0.001$) were also significant, neighbour effects were marginally significant ($P = 0.1$), and row effects were not significant ($P = 0.5$). Paired t-tests revealed significant differences ($P = 0.03$) between the results from line 1 to line 3 .

Similarly, the results from the three lines differed significantly ($P = 0.05$, ANOVA). Lines 1 and 2 did not differ significantly ($P = 0.90$, t-test), but lines 1 and 3 and 2 and 3 (Fig. 64) did. The numbers of pueruli caught per collector in lines 1, 2, and 3 (SE in parentheses) were 3.64 (0.64), 3.51 (0.67), and 2.17 (0.41). The numbers of pueruli caught by collectors having 2, 3, and 4 neighbours (SE in parentheses) were 1.22 (0.43), 3.33 (0.47), and 3.32 (0.59). Neighbour effects were significant ($P = 0.07$) when collectors with 3 and 4 neighbours were compared with those with 2. The number of pueruli caught by corner collectors was 1.22 (0.37); the number caught by all other collectors was 3.33 (0.43).

3.3.4 Size of collector

Collector size and catch appear to be linearly related (Fig. 15). The slope of line (a) of Fig. 73 is 7.51 ($P < 0.001$), that of line (b) is 1.81 ($P < 0.001$). The settlement rate in September and October was about 2.3 times that in the other months. Catches of different-sized collectors were not affected by the settlement rate. Similar results (not shown) were found in the analysis of the catch data for different-sized purse collectors.

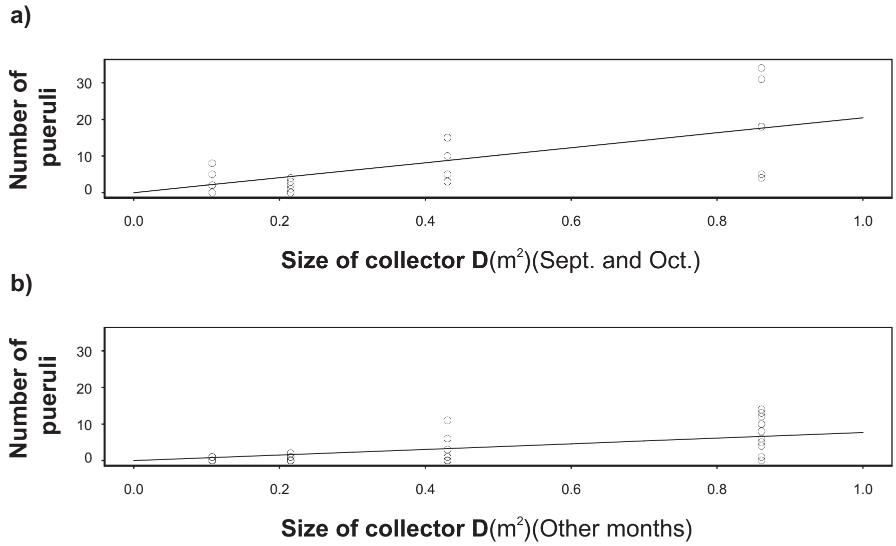

Figure 73. Plots of number of pueruli against size of collector D at Seven Mile Beach. **a)** September/October 1999 (*N* =23) and **b)** August, November, December 1999 and January 2000 (*N* = 33).

3.3.5 Frequency of collector servicing

The effects of frequency of collector servicing on puerulus catches are shown in Table 37.

Table 37. Number of pueruli caught in November, December, and January lunar months (mean and standard deviation) with different frequencies of servicing.

Sampling frequency	November 1999	December 1999	January 2000
Seven times per month (near new moon)	1.13 (1.06)	2.27 (1.28)	0.07(0.27)
Once per month (Full moon)	0.47 (0.74)	0.80 (1.15)	0.31(0.60)
Power of test	0.51	0.99	0.29

We carried out a power analysis to determine whether the sample sizes warranted comparing the results from the two sampling regimes. A power level of at least 0.8 would ensure that a t-test would have a low risk of Type II error. The power value was 0.29 for the t-test for January 2000 and 0.51 for November 1999. All the coefficients of variation from collectors checked monthly were greater than 1.0, and those for data from the frequently checked collectors were less than 1.0, with the exception of the January 2000 data. The January data were therefore unreliable because of the low catch rates in that month, and they were excluded from further analysis.

An ANOVA testing the catches of pueruli under different servicing conditions showed that the effects of treatment ($P < 0.001$) and time ($P = 0.01$) were significant but that the effects of block ($P = 0.77$) and other higher-order interactions ($P > 0.15$) were not. The ratio of catch of pueruli on the frequently serviced collectors to catch on those serviced monthly was 2.7:1.

3.4 Discussion

We have (i) tested modified western rock lobster sandwich collectors at different depths and distances offshore, (ii) tested different collector designs, (iii) examined the effect of collector size, and (iv) tested the effect of frequency of servicing the collectors. The only catches recorded in the onshore-offshore trials were on gear set at the inshore site (depths <5 m)

3.4.1 Collector designs

The results of the trial that compared catch on sandwich collectors at different depths and distances offshore were conclusive; only surface collectors set in shallow inshore waters caught pueruli.

Phillips collectors are normally set at the surface in inshore areas, principally because in such shallow waters (3–5 m) surface deployment prevents contact with the bottom and because they are too fragile to be set outside reefs. Surface collectors have not necessarily been the most successful for catching pueruli of species like *Jasus edwardsii* (Booth *et al*. 1991); *Panulirus homarus homarus*, *P. ornatus*, and *P. polyphagus* (Tholasilingam and Rangarajan 1986); and *P. argus* (Heatwole *et al.* 1991), but inshore sites have generally been the most successful for catching pueruli of a range of species, e.g. *P. interruptus* (Serfling and Ford 1975), *P. argus* (Heatwole *et al*. 1991), and *J. edwardsii* (Booth *et al*. 1991).

The sandwich collector used in our study has proved to be a robust, medium cost design that is easy to service with the appropriate equipment. Catch rates of *P. cygnus* pueruli by sandwich collectors under different settlement densities have yet to be compared with those of the more commonly used Phillips collector.

The gear trials in our study suggest the importance of conditioning tassels made from Kinnears fibre before use, although the optimal conditioning duration has yet to be determined. This result is of interest, because in earlier years tassel collectors for catching *P. cygnus* were made of Tanikalon fibres, which did not require conditioning (Phillips personal communication, quoted by Phillips and Booth 1994). Some results reported here may underestimate puerulus catch rates because the fibre used on the collectors was not sufficiently conditioned before use.

3.4.2 Cost of Construction and General comments on collectors.

Below Table 38 is a summary of the estimated cost of construction of each of the various types of collectors in 1998 (these will vary depending upon labour component at site of fabrication). No costing have been carried out on the mooring equipment employed (e.g. type of mooring, swivels, chains, shackles etc) as these are governed by location, substrate and depth etc.

Table 38. Cost to construct the various types of collectors used in this experiment.

Type of collector		Cost $Aus
Phillips		204
Sandwich	Gaint	244
	Normal	122
	Half	66
	Quarter	33
Whitam		69
Mills		20
Purse	(0.25 m^2)	15
	(1.0 m^2)	43
	(1.5 m^2)	60
Rossbach		40

Not only the cost of construction should be considered but also its robustness (i.e. ability to handle the extremes of environmental conditions), its life expectancy and how easy it is to work on a vessel etc.

The Mills collector was by far the cheapest to construct at $20 per unit (Table 38), and servicing was easy because of its light weight and use of cable ties. The Witham was extremely easy to service, but construction costs of $69 made it the third most expensive of the five types tested. The Rossbach vertical collectors were inexpensive to construct and were easy to service. The horizontal collectors were more difficult to service and reset because two moorings were required.

Purse collectors, depending upon size, were easy and cheap to fabricate. As size increased, so did the degree of difficulty in servicing them. The purse and Mills collectors were easily damaged; the mesh could be ripped on sharp objects, and too much pressure could be applied during retrieval under adverse weather conditions. Sandwich collectors, although the most expensive to construct, withstood the rougher conditions and were easy to service, although special equipment was required for spinning the collector to remove the pueruli and post pueruli.

3.4.3 Collector interactions

The results from comparisons of catches by neighbouring collectors in the array were unexpected and potentially hold far-reaching consequences for the placement of research puerulus collectors used for predicting rock lobster catches (Caputi *et al*. 1995a, b; Melville-Smith *et al*. 2001) and for commercial collectors should they become a reality in the future.

Because collectors on the outer edge of the experimental design, and corner collectors in particular, had significantly lower catch rates than other collectors, a single collector without any neighbours would have the least likelihood of catching large numbers of pueruli. The data collected in 1971 and 1972 (Phillips and Hall 1978) produced results similar to this study. It is clear from our study, in which collectors were set five metres apart, that neighbouring collectors improve the overall catch of pueruli, but further work will be necessary to establish the optimal distance between collectors. The reasons for the neighbour effects remain unknown.

3.4.4 Servicing of collectors

Like neighbour effects, the difference in catch between frequently service collectors and collectors serviced monthly near full moon will have important implications for commercial puerulus harvesters in the future. The potential commercial benefits of a more than doubled catch at high servicing rates must be weighed against the costs of the other strategy–more collectors, serviced only monthly.

The higher puerulus catch of frequently serviced collectors indicates either that some pueruli leave the collectors after settling or that mortality of pueruli takes place on the collectors. Previous work (Phillips personal communication, quoted by Phillips and Booth 1994) found no difference in the number of pueruli caught by frequently and infrequently serviced collectors. Again, the type of fibres used for the collectors may be important.

3.4.5 Effect of collector size on settlement

Comparisons of different-sized collectors of the same type show that catch rates are related to collector size. The limited number of observations and size ranges for collectors in our study suggest that, for sandwich collectors, the relationship between catch rate and collector size is linear. Although catch rates for purse collectors were also related to size, the relationship was less clear.

Although larger collectors caught more pueruli, the difficulty of servicing these larger collectors prevented our using them in further testing. However, a commercial operator may find a way of operating these or even larger collectors.

Trials to determine the best methods of capturing large numbers of pueruli continue. Current tests include examination of localised variability in catch rates over a scale of several kilometres, discussed later in this report.

3.5 Conclusions and recommendations

The optimal distance between collectors for maximizing catches of *P. cygnus* is unknown, and further studies are needed, but a single collector is clearly not an effective catching unit. The corner and carry-over effects demonstrated here make clear that future studies comparing collector types will need at least two lines of collectors and at least twice that number of columns (i.e., at least eight collectors per trial), and during the trial the collectors must be repositioned as shown in Fig. 70. If the purpose of the trial is to produce data of sufficient accuracy to allow conversion rates of the catches of different collector types, then either high catch rates or an extended period of trials will be necessary.

Testing of collectors is only practical at times of high settlement. At other times the results are unreliable because the variation in catch between collectors is likely to be very high. Coefficients of variation and power tests should be used so that the results will not be misleading. Any data with a coefficient of variation greater than 1.0 should be handled carefully.

4. CHAPTER 4
Alternative pueruli harvesting methods trialled

In addition to the testing the effect of different collector types, sizes and arrays on collector catch rates (discussed in Chapters 3), we have also examined whether fixed nets, pump nets and a mid-water trawl net could be used as an alternative to the more traditional collection methods of catching pueruli.

4.1 Pump nets

A water-jet sledge, based on the design used by Penn and Stalker (1975), was tested at Seven Mile Beach. The frame was 810 mm long*500 mm wide *350 mm deep made of galvanized water pipe (25 mm diameter) with skis (100 mm wide*5 mm thick) lined with marine ply. A central T shaped bar had 3 mm holes drilled every 50 mm through which water was pumped by a "Finsbury" centrifugal pump driven by a 5.5 -hp "Honda" engine. The net, which covered the entire frame was made of 2 mm nylon (nytal) netting. The pump was carried in the boat and the sledge was lowered onto the bottom substrate and then pulled on the port quarter of the vessel to avoid turbulence created by the propeller whilst towing.

Sampling was carried out opportunistically over the new moon period and as the weather conditions permitted, between July and December, 2000. The sledge was towed over sand/weed substrate to avoid snagging the net on reef/rock bottom, for durations of 15 minutes and at sufficient speed to maintain headway whilst not lifting the sledge off the bottom. Towing for periods greater than 15 minutes led to the net becoming clogged with sand/weed etc with the result that the sledge would become bogged on the bottom and act as an anchor. Once towing ceased the net was pulled on board, rinsed down and the sample poured and filtered through a fine mesh sieve.

The water-jet sledge was also tested on the September 2000 R.V."Flinders" cruise off Dongara. The net was lowered over the stern of the vessel until it reached the bottom and the vessel was allowed to make headway. Three shots were conducted in shallow water near Dongara in 10-12 m of water.

4.2 Fixed nets

A fixed net (1 m*0.5 m stretched over a stainless steel frame) was set immediately behind the reef break at Seven Mile Beach, between September and December 2000. The net was left overnight on six occasions (around the new moon phase) and pulled at first light. Doherty and McIlwain (1996) using similar fixed nets to those deployed in this study reported catching small numbers of pueruli near the reef system at Ningaloo Reef, W.A. using fixed nets set near the reef system, similar methods to those trialled in this study.

4.3 Mid-water trawl nets

A mid-water trawl net was trialled using the R.V. "Flinders"over the new moon period in September 2000. Work was undertaken from near the Abrolhos Islands to inshore adjacent to Dongara (near Seven Mile Beach see Fig. 74). From previous studies (Phillips 1977), late stage phyllosoma and puerulus larvae of the Western Rock Lobster have been caught in the area in which we trialled the gear.

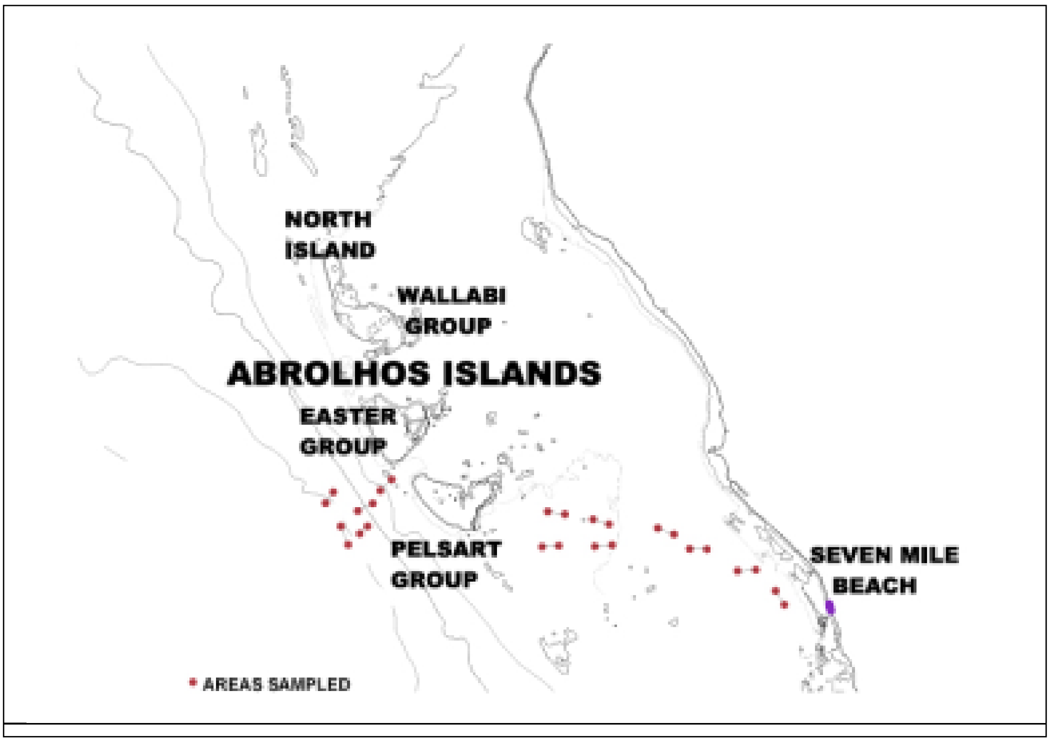

Figure 74. Area where both plankton and mid-water trawl nets were trialled in September 2000 (red dots).

A mid-water pelagic trawl net (manufactured by H.S.Vodbinder of Denmark) was used. The mid-water trawl net had a working mouth size of approximately 11.5 m X 9.5 m which was modified to catch puerulus by the insertion of a fine mesh lining (500 X 400 meshes X 9 mm mesh size) to prevent these small animals passing through (Fig 75). The net was towed astern at various locations and at depths ranging from 10-25 m over several nights. The net was deployed at each location for one hour towing at an approximate speed of 2.5 knots for an average distance of 2.4 nautical miles. The net was winched on board and then washed down with a high-pressure hose to ensure that sample was washed to the cod-end before being sieved. All the samples were frozen in liquid nitrogen immediately after capture.

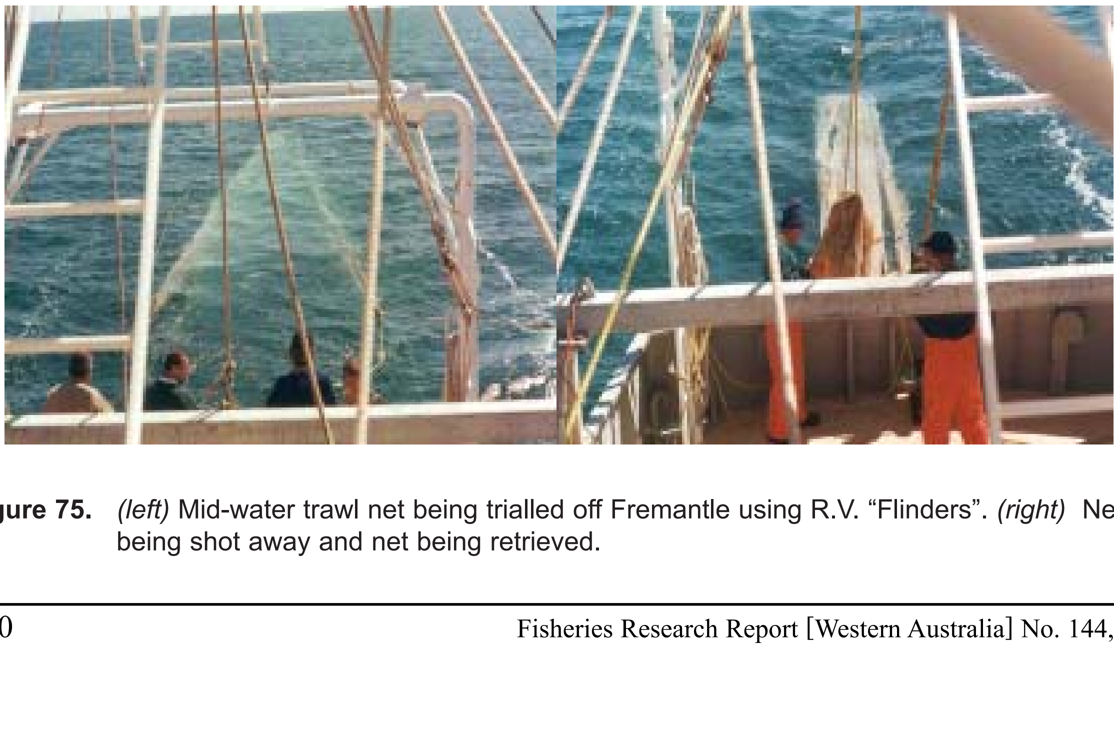

Figure 75. *(left)* Mid-water trawl net being trialled off Fremantle using R.V. "Flinders". *(right)* Net being shot away and net being retrieved.

4.4 Results and Discussion

4.4.1 Fixed and pump nets

Neither the fixed nor pump nets caught any quantity of pueruli during trials. The water-jet sledge was marginally more successful than the fixed nets and caught two pueruli during September 2000. However, it is not possible to establish whether the pueruli were caught whilst the net was on the bottom, or mid-water or whilst it was being retrieved. Either of these two methods discussed above could be modified to increase the dimensions of either the net or sledge size to provide larger catching potential. Regardless of size of the net or sledge, the timing of effort in relation to puerulus settlement peaks should be considered as extremely important in attempting to catching large numbers of pueruli.

4.4.2 Mid water trawl nets and plankton tows

Table 39. Station locations and puerulus caught in September 2000

Station	Date	Water depth (m)	Net depth (m)	Distance hauled (n miles)	Puerulus caught
1	26/9/00	63.2	21.0	2.31	2
2	26/9/00	60.0	20	2.44	7
3	26/9/00	53	20	2.35	1
4	27/9/00	55	25	2.44	6
5	27/9/00	510-720	10	2.38	5
6	27/9/00	56-137	10	2.52	16
7	28/9/00	44-46	20	2.46	2
8	28/9/00	43-46	20	2.34	0
9	29/9/00	37-38	10	2.50	0
10	29/9/00	33	20	2.48	16

As can be seen from Table 39, catches were low in numbers, regardless of the area and water depth sampled. When one takes into account the cost in fuel and time of towing these large mid-water nets and the amount of ground covered and the amount of water filtered, it appears to be an uneconomical method to adopt.

Plankton tows were also conducted in the deeper water (725-1000 m depth) west of the Abrolhos Islands (near the Southern Group), in an attempt to catch both puerulus and phyllosoma over the new moon phase. Each tow was one hour in duration and the net used was a standard Bongo plankton net using 500 µm mesh (as described in FRDC report 92/95). All nets were hosed down and the contents of the cod-ends placed into plastic bags and then frozen in liquid nitrogen. Samples of phyllosoma and pueruli that were obtained on the cruise have been sent to CSIRO Marine Research, Hobart under a collaborative research arrangement. The lipid levels of those pueruli will be measured to examine variation in lipid content during their inshore migration, which still need to be concluded.

5. CHAPTER 5

The effect of collector position on localised western rock lobster puerulus catch rates at Shark Bay and Seven Mile Beach, Western Australia

5.1 Introduction

Two experiments were run concurrently at Seven Mile Beach and Shark Bay from July to December 2000. The primary objective of both experiments was to determine whether there are localized variations in the catch rates of pueruli collectors. The opportunity also arose to investigate the impact of using different backing materials (i.e. different colour and weave) on the collectors and to see if this had any influence on their pueruli catch rates.

In the case of the experiment at Seven Mile Beach the arrays of experimental collectors were spread over a length of coastline spanning approximately 3 km (Fig 70, Chapter 3.) and were kept at the same sites for the duration of the experiment. At Shark Bay the arrays of pueruli collectors covered a much smaller length of coastline and were moved each month of the experiment in response to collector catch rates.

5.2 Methods

The Sandwich - type collectors were used in the experiments with two sheets of tassels back-to-back, each with dimensions 615x350mm (see Phillips *et al*. in press). There were two types of collector configurations, both were identical except for the colour and weave of the backing cloth which covers the PVC boards to which are attached the polypropylene tassel fibres. Collectors with the new type of backing cloth that had a white and slightly coarser weave backing cloth have been termed 'white' throughout these trials. This backing is produced by Southcorp Industrial Textiles called "Canvacon"- 7000Q being an uncoated white polyethylene weave matting. Collectors with the type of backing cloth that has been traditionally used, i.e. a brown and slightly finer weave have been termed 'brown' in this report. Unfortunately this fibre is no longer manufactured and we do not have a manufacturers name.

In the experiment at Seven Mile Beach, 26 white and 37 brown collectors were arranged into groups of four, such that two were white and two were brown. Due to the number of collectors available it was not possible to design all groups with an equal number of white and brown collectors and so some were made up entirely of one type. All collectors remained moored in the same place for the duration of the experiment.

The experiment at Shark Bay was designed somewhat differently to that at Seven Mile Beach, in that the arrays of collectors were set up in an 'H' configuration and were moved each month in the direction of that part of the 'H' in which collectors achieved the highest catch rates. Due to bad weather, in particular large swell conditions, it was not possible to pull all collectors each month. As a result, none of the 32 collectors were examined in July or September and only nine were examined in August, 28 in October, six in November and 24 in December.

All collectors were checked once per month over the full moon. This involved servicing the collectors as previously described in Chapter 3. Three response variables were measured, namely (i) puerulus (ii) juveniles, i.e. pueruli that had moulted and (iii) stragglers, i.e. juveniles of a size that indicated that they had settled in the previous month. The treatments of interest in this experiment were time, collector type, location and carry over effect. Carry over effect is the response that neighbouring collectors have on each others pueruli catch rates. Specifically, we tested the effect that collectors on the seaward side of an experimental group of four collectors, have on those 10 m away on the shoreward side of the group (Fig 76). The assumption has been made that since pueruli swim inshore, that collectors on the seaward side of the group of collectors should be unaffected by carry over effects.

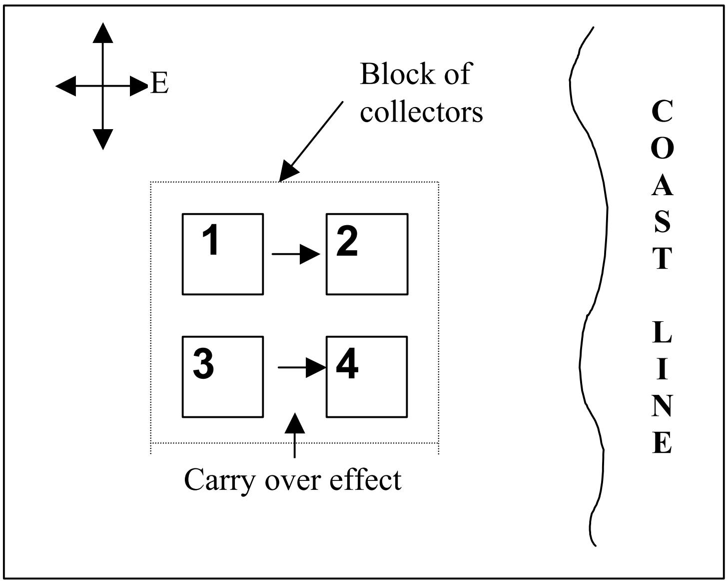

Figure 76. Illustration of what is termed a block of collectors. As illustrated, collectors 1 and 3 have a carry over effect on collectors 2 and 4, respectively.

In this part of the analysis we determined the total number of pueruli collected by a particular collector for some month, to be the sum of the pueruli and juveniles collected that month, plus the number of stragglers determined to have been in that collector in the proceeding month. We performed a similar analysis to that in the proceeding section.

Let a particular response of collector u at location ℓ at time t be denoted by:

$$Y_{u,\ell,t} = \alpha_t + \beta_{u,u-1} + \rho_u + E_{u,\ell,t}$$

where

α_t is the effect of time on the puerulus settlement (assumed to be a polynomial of order 2);

$\beta_{u,u-1}$ is the carry-over effect for collector u from collector u-1, where
$\beta_{u,u-1} = \lambda I_{u-1} Y_{u-1,\ell,t}$;

$$I_{u-1} = \begin{cases} 1, \text{if } u = 2,4 \\ 0, \text{otherwise} \end{cases}$$

ρ_u is the collector type effect; and
$E_{u,\ell,t} \sim N(0,\sigma^2), \forall u,\ell,t$ and $Cov(E_{u_1,\ell_1,t_1}, E_{u_2,\ell_2,t_2}) = 0, (u_1,\ell_1,t_1) \neq (u_2,\ell_2,t_2)$.

For the Seven Mile Beach experiment, collector 44 (tag no) was lost and thus had no recorded data for the entirety of the experiment and hence, was eliminated from the experiment. Collector 65 had data recorded for November and December but not the other remaining four months. Whilst collector 42 was found washed up on the beach in November and hence had no observation taken for that month. For these two latter collectors we required a method for replacing the missing data.

Missing data for a particular location, assuming no carry-over effect, was replaced with the following estimate (Cox, 1954):

$$\frac{mM + tT - G}{(m-1)(t-1)}$$

where

m is the duration of the experiment in months (six);

t is the number of collector types (two);

T is the sum of all observations for a particular collector type, excluding missing observations for that collector type, for a particular location;

M is the total of all observations in the same months for which there are missing observations, for a particular location; and

G is the sum of observations for a particular location over the duration of the experiment, for a particular location.

For each missing observation estimated, 1 was deducted from the error term degree of freedom.

The catch rate of brown and white backing type collectors were summed for particular blocks and were compared using a paired t-test. Collector blocks 1, 4, 12, 13 and 16 were not used in this part of the analysis because they did not contain two of each type of collector.

Locational effect is comprised of both longshore position and localized effects, both of which were not possible to test within the split plot analysis.

Longshore position effect was tested using a linear regression of catch rates versus location. Over a short length of coastline for which we are dealing (approx. 3 km)a linear regression was seen as being suitable. This regression test was performed for each month of the trial.

Localized effects of each site were tested by performing paired t-tests comparing mean catch rates at each location at each point in time.

5.3 Results

Shark Bay

Due to the failure to collect sufficient data as a result of adverse weather conditions which caused sampling problems and loss of gear, the full analysis described in Methods (above) could not be performed on the Shark Bay data. Using those data that were suitable for analysis a paired t-test of the mean of the brown and white collector types at Shark Bay showed that there was insufficient evidence to confirm a difference in their performance ($p = 0.15$). This result is evidenced in Table 40 and Figure 77.

Table 40. The mean (s.e.) of the number of puerulus collected by a particular collector type each month, at Shark Bay. No data was collected in July and September.

Month	Collector	Backing type
	Brown	White
July	na	na
Aug	3.4 (1.1)	2.8 (0.7)
Sep	na	na
Oct	7.0 (1.5)	9.2 (0.9)
Nov	7.7 (2.2)	11.3 (3.1)
Dec	4.8 (0.8)	6.5 (1.4)

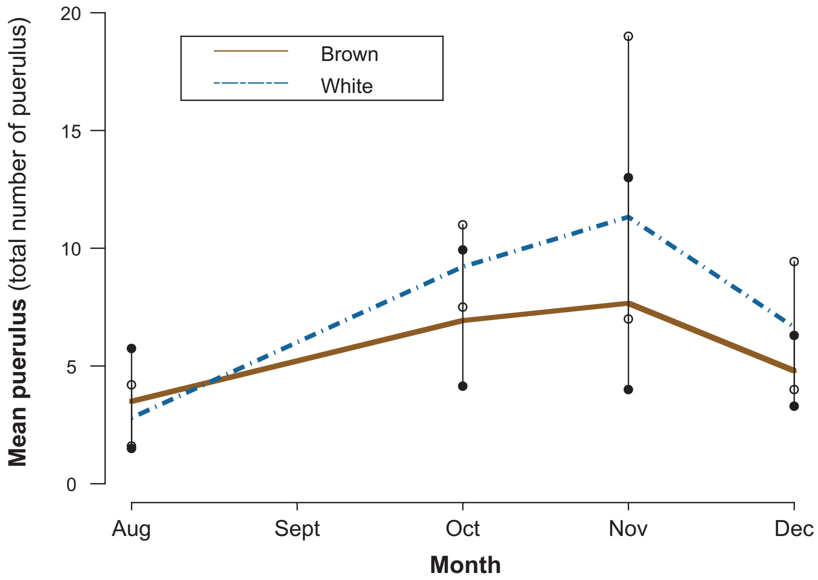

Figure 77. Plot of the mean number of puerulus collected of *Panulirus cygnus* by each collector type, for each month, in Shark Bay. 95% C.I.'s are also included.

Seven Mile Beach

Performing a paired t-test of the two collector types within the same block shows that the old (brown) collector backing out-performed new (white) collector backing ($p = 0.00$), with a sample mean difference of 8.94 animals per block (i.e. two collectors of the brown backing type collected 8.94 additional animals compared to the same number of the white backing type within the same block). This result is shown in Fig 78.

Table 41*. The mean (s.e.) for the total number of puerulus caught by collectors over time, for each type of collector used in the Seven Mile Beach experiment.

Month	Brown	White
July	0.70 (1.2)	0.27 (0.5)
Aug	3.30 (2.2)	1.96 (2.0)
Sept	10.30 (6.3)	6.92 (3.2)
Oct	15.49 (6.4)	11.19 (4.8)
Nov	10.27 (5.7)	7.96 (5.3)
Dec	8.08 (5.1)	5.65 (3.5)

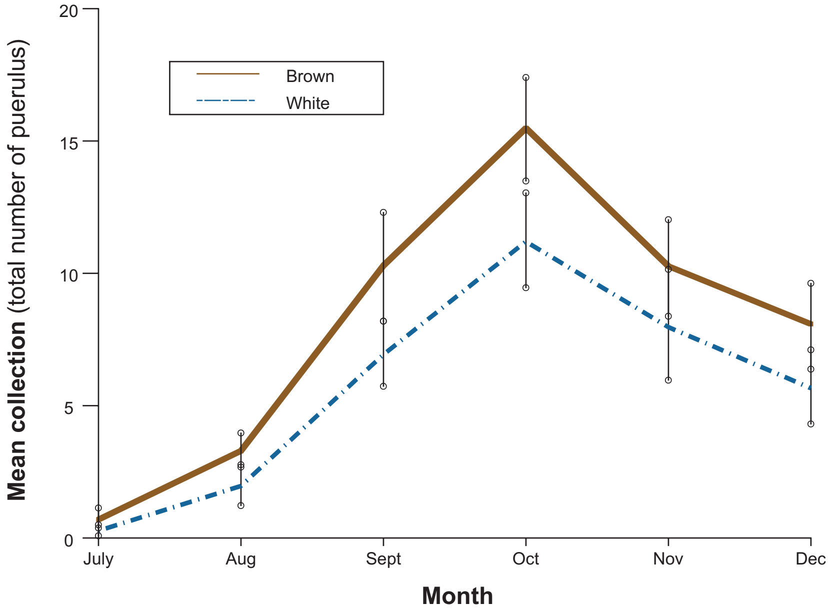

Figure 78. The mean (st.dev) for the total number of puerulus of *Panulirus cygnus* caught by collectors over time, for each type of collector used in the Seven Mile Beach experiment.

The effect of the longshore position of individual collectors on puerulus catch rates is shown in Fig. 79 for each month over the study period. Linear regressions were run for the mean number of puerulus collected each month by each collector. The minimum and maximum totals indicate that the totals seem to be normally distributed.

The results (Table 42), show that apart from December (p = 0.00), the p-value for all other gradients were non-significant (p>0.14). Accordingly, it can be concluded that the variation in catch rates over that part of the coastal line covered by this study was not uniform in terms of longshore direction. Due to localized effects it should not be unexpected that there are sudden departures from linearity in testing for longshore effects. This is evident in figure 79, where it can be seen that some sites consistently caught less than other sites either side. Such aberrations are assumed to be due to varying bottom substrate type for which sufficient information does not exist to be included in our model. It should also be noted that the collector sampling locations were not equally spaced across the study area and it was therefore not possible to test for autocorrelation.

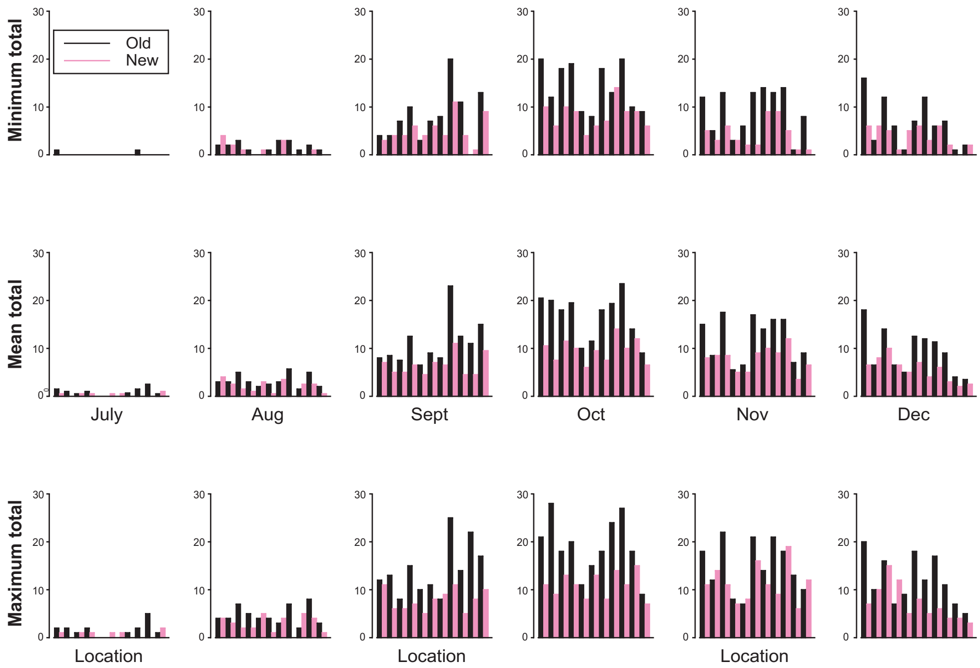

Figure 79. Plot of the minimum, mean and maximum number of total puerulus of *Panulirus cygnus* collected by each collector type, at each location, for each month of the Seven Mile Beach experiment.

Table 42. The results of a simple linear regression of the collection of puerulus by various locations against their location, for each month of the Seven Mile Beach experiment. These include the p-value for the gradient.

Month	Const	Grad	p	mean	st.d	min	max
July	0.38	0.02	0.54	0.45	0.80	0	4
Aug	2.57	0.02	0.73	2.66	2.11	0	9
Sept	7.47	0.15	0.26	9.05	5.40	0	25
Oct	15.80	-0.25	0.14	13.77	6.16	0	28
Nov	10.21	-0.11	0.49	9.29	5.66	1	22
Dec	10.14	-0.36	0.00	7.08	4.67	0	20

The fact that there was no trend in longshore catch rate is not unexpected, because the experiment only covered approximately 3 km of coastline. Given the variance in the catch rates of individual collectors, any directional trend would have been unexpected over such a short stretch of coastline. It was considered that a far more likely effect might be for particular blocks of collectors to consistently perform ether better or worse than others in the experiment. We have called these localized non-uniform catch variations.

Since the split-plot design was not capable of testing for localized effects, paired t-tests were used to compare mean catch rates at each location at each point in time (Table 43). Once again, the analysis was constrained to only comparing those locations that used equal replicates of collector types (i.e. two brown backing type and two white backing type).

Table 43. P-values for the paired t-tests of those locations (blocks) that had an equal replicate of collector types, for the Seven Mile Beach experiment.

Block	2	3	5	6	7	8	10	11	12	14	15
2	1.00	0.04	0.54	0.18	0.02	0.21	0.27	0.69	0.53	0.14	0.20
3	0.04	1.00	0.13	0.88	0.05	0.63	0.06	0.23	0.17	0.38	0.52
5	0.54	0.13	1.00	0.32	0.04	0.24	0.26	0.83	0.70	0.22	0.26
6	0.18	0.88	0.32	1.00	0.15	0.70	0.04	0.35	0.35	0.35	0.54
7	0.02	0.05	0.04	0.15	1.00	0.08	0.03	0.08	0.01	0.27	0.47
8	0.21	0.63	0.24	0.70	0.08	1.00	0.09	0.55	0.51	0.46	0.35
10	0.27	0.06	0.26	0.04	0.03	0.09	1.00	0.14	0.13	0.04	0.01
11	0.69	0.23	0.83	0.35	0.08	0.55	0.14	1.00	0.90	0.19	0.23
12	0.53	0.17	0.70	0.35	0.01	0.51	0.13	0.90	1.00	0.14	0.16
14	0.14	0.38	0.22	0.35	0.27	0.46	0.04	0.19	0.14	1.00	0.89
15	0.20	0.52	0.26	0.54	0.47	0.35	0.01	0.23	0.16	0.89	1.00

Referring to Table 43 it is evident that blocks 7 and 10 tend to perform differently to other blocks . These blocks in fact, are those that perform less well than those other blocks as indicated in Figure 80.

Neighbourhood effects (as described in Phillips et al., in press) were shown to exist ($p = 0.02$) between individual collectors within a block. The correlation of the total number of puerulus with associated carry over effect was 0.30 ($p = 0.00$). The total puerulus carry-over effects indicates that collectors 1 and 3 (Fig.76) would be likely to collect more juveniles than collectors 2 and 4.

5.4 Discussion

The catch rates of the two collector types were not significantly different when they were compared at Shark Bay ($p = 0.15$), but they were significantly different when they were compared at Seven Mile Beach ($p = 0.00$). The reason for the difference in the result from the two areas is likely to be because the collectors that were used at Shark Bay were specifically constructed for the experiment and had never been used before.

In contrast, the collectors that were compared at the Seven Mile Beach site were made up of some collectors that had been used in the previous season, and were therefore in effect preconditioned prior to the start of the experiment, and others that had not been used before. The used collectors had old backing while the newly constructed ones had new backing material. It is accepted from previous work (Phillips et al in press) that puerulus catch rates are affected by a period of conditioning prior to their use. It was therefore expected that the collectors with old type of backing might have had better catch rates than those with the new white type of backing in the first few months of the trial until the newly constructed collectors had fully conditioned. However, it is clear from the results (Fig. 78) that collectors with the brown type of backing caught consistently better than those with the white type of backing, even six months after the start of the experiment. It therefore remains unresolved whether the difference in catch rates at Seven Mile Beach between collectors with brown compared to white style backing is due to the effects of the backing material or conditioning.

Since there was no significant difference between the old and new types of backing material in the trial conducted at Shark Bay where the result was not confounded by differences in collector conditioning times, it would seem that the differences in catch rates of the two types of collectors at Seven Mile Beach is due to conditioning rather than the type of backing used. This result does emphasize our lack of understanding about the effect of conditioning time on catch rates of collectors with polyethylene split fibre tassels manufactured by “Kinnears Pty Ltd” and the need for more research on this subject.

Apart from December (p=0.00), it was concluded that there was no coastal linear trend of puerulus collection (p>0.14) at Seven Mile Beach (Table 43). However, it is apparent from Table 43 that some sites tended to perform better than others. The reason for these differences are not clear, but they are likely to be due to some collectors being more exposed to pueruli swimming inshore because of their position relative to localized water movements. This theory is supported by the observation that there is a correlation between the number of juveniles/pueruli on the same site over successive months (r=0.75). This indicates that localized effects which are attractive to settling pueruli hold for extended periods.

6. CHAPTER 6

Protocol for catching large numbers of pueruli and post pueruli of *Panulirus cygnus* and *Jasus edwardsii*

6.1 Methods available to catch pueruli and post pueruli

Pueruli are the post larval stage of rock lobsters which settle out of the plankton and the end of the oceanic phase in the life cycle. Post-pueruli are small juvenile rock lobsters (maximum carapace size 30 mm) which have recently moulted from the settling puerulus stage. There are a number of methods available to catch pueruli, including diving, nets, trawling, and collectors. What is required is a method that catches as large a number of pueruli as possible, and at a minimum cost. This technique will vary depending upon which species of rock lobster is targeted.

6.1.1 Equipment

Collectors have generally proven the best method of capture, mainly because they operate without the need for human attention between servicing periods. Several types of collectors could be used, but the best type will depend on the area in which they are to be set and the level of funding available.

For *Panulirus cygnus*, the sandwich collector is suitable for most situations and is effective, robust and easy to service. The sandwich collector is described in Appendix 2 of this report.

For *Jasus edwardsii*, the bottlebrush collector has been recommended as described in Chapter 2, complete with heavy mooring system to accommodate the extreme weather conditions found on the southern Australian coastline. Mesh (Mills) collectors may prove an economic alternative, if mesh used in the collector can be sourced as derelict fishing nets.

6.1.2 Time of year

For *Panulirus cygnus,* settlement varies annually, but the maximum catches on collectors have occurred between September and January. This means that the equipment needs to be set out in June/July (2-3 months for conditioning) and recovered after the peak in February.

For *Jasus edwardsii ,* settlement varies annually, but maximum catches on collectors have occurred in two clear peaks around August/September and December/January. This means that the equipment needs to be set out in May/June (2-3 months for conditioning) and recovered after the peak in February.

6.1.3 Site selection

Sites for *Panulirus cygnus* collection should be near shore, and have a coastal reef system on their seaward side. This will provide protection from ocean storms and permit checking on a regular basis in most conditions. The distance offshore will vary from site to site depending on the configuration of coastal reefs, but in most cases is likely to be less than 500 m. In

Western Australia site selection will have to be made after discussions with the Department of Fisheries, local fishers, the Department of Transport, and other relevant authorities. This is to ensure a successful site for capture of pueruli, and one which does not interfere with other marine activities in the area.

Because of Tasmania's exposed coast line, sites for *J. edwardsii* collection need to provide as much shelter as possible, while still receiving a direct input of oceanic water. Permit conditions for commercial collection in Tasmania require that a 'Harvest Plan' be approved by the Director of Marine Resources (State Department of Primary Industry, Water and Environment). The plan must include details of areas where collection will take place, method of collection, number of collectors and details of the grow-out facility.

6.1.4 Setting equipment

For *Panulirus cygnus*, the collectors can be assembled ashore and transported to the site by road or sea. Collectors can be individually positioned within a site by attaching the chain to the mooring weight, placing this in the correct position, and then measuring the necessary chain needed to hold the collector. The chain can then be cut, attached to the swivel below the collector, and the collector can then be released into the water.

Collectors should first be positioned along the coast in the area of interest, to identify areas with highest catches. It is important to realize the catches of individual collectors will be less than collectors set out in an array (studies have shown that neighbouring collectors improve the overall catch rate of an array of collectors), hence the catches of a long line of collectors may identify area of increased catches, but not the level of catches that collectors set out in an array may achieve. Once areas of best catches have been located, the collectors should be set out in an array about 5 m apart, probably in lines parallel to the shore. However, other configurations may be more effective.

For *Jasus edwardsii,* , the collectors can be assembled ashore and transported to the site by road or sea. The light weight and small size of bottle brush and mesh type collectors means that they are suited for deployment on bottom-set long lines or chains, a feature that can substantially increase the rate of servicing. Such lines must be well anchored at each end, and possibly at intermediate points, depending on the length of lines. While trial collectors were serviced by divers, surface hauled systems can readily be devised, and are currently being used by some commercial operators, eliminating the cost of diving. Keeping collectors at heights of less than 1.5m from the seafloor in water depths of 6 to 15 m will maximise catch rates.

6.1.5 Checking and equipment

For *Panulirus cygnus*, settlement is mainly confined to about 10 days around new moon. However, it has been shown that daily checking of collectors for about seven days near moon can increase the catches by over 100%.

To service, collectors need to be removed from the water and pulled into the vessel. The spinning shaft is then slid into the central holes in the wood braces. The whole unit is then placed inside a large tub over which a plastic cover is placed and the sandwich is rotated both clockwise and counter-clockwise 20 times. For large-scale operations a device with an electric motor fitted in a similar fashion to that of a chicken rotisserie would speed up the process of sampling. The sample obtained is then poured into a sieve, sorted and the pueruli collected.

Settlement of *J. edwardsii* pueruli seems largely determined by water movements, and there is no detectable lunar periodicity. It appears that some pueruli will leave collectors after settling, so frequent (weekly or less) servicing is recommended in periods of high settlement. Bottle brush collectors are serviced by hauling them on board the vessel, and shaking vigorously over a large tub. To reduce the spread of sediment from collectors as they are shaken, they can be placed inside a simple plastic shroud open only at the bottom. For mesh type collectors, the mesh is removed from the cube frame, shaken over a tub, and replaced in the frame. Contents of the tub are periodically poured through a sieve to remove pueruli.

6.1.6 Costs

Costs of producing limited numbers of collectors for scientific trials are included here only to give an indication of relative costs of collector materials. It is likely that considerable savings can be made when mass producing collectors for commercial deployment.

Table 44. Cost of each type of collector and time required for construction.

Collector Type	Material cost	Construction time
Bottle Brush	$18	40min
Mesh	$12 - $30*	25min
Sandwich	$120	75min

*If collector mesh is sourced as derelict fishing gear, cost of mesh collector is reduced to $12.

6.1.7 Number of pueruli

The rate of *Panulirus cygnus* settlement in Western Australia is much higher than that of other Australian species.

Puerulus settlement levels vary from year to year and area to area. Catches of individual collectors set in areas of the Western Australian coast where settlement of *P. cygnus* is high usually average 100 animals per month during peak settlement. However, they may be less than this, or as high as 450 in a single month during peak settlement periods.

The maximum catch of *J. edwardsii* pueruli from a bottlebrush collector (see T.A.F.I. website, page 100 of this report for description of the various collectors used) in Tasmania during 3 years of collector trials was 57, coinciding with an average for that month of 35 pueruli per collector. This is similar to maximum numbers recorded from scientific crevice collectors in Tasmania. Long term averages over the 9 months when commercial operators would have collectors in the water are 7 to 9 pueruli/collector/month, at good collection sites.

6.1.8 Transporting pueruli and post-pueruli

Pueruli and post-pueruli of both species are relatively tough animals. They can be easily transported in insulated containers with some form of aeration to the water. Battery or other small electric pumps are available cheaply.

Care should be taken to see the containers are kept out of the extremes of the prevailing weather conditions (hot or cold), to prevent temperature stress. After reaching the final location, the animals should be kept in the containers until the water temperature in the containers equilibrates to the temperature in which the animals are to be held before being released into their new surroundings.

6.1.9 Other alternatives

Although we have recommended the sandwich collector for *Panulirus cygnus*, other options could be possible. The results of the collector tests clearly showed that the catches were related to collector size. Because we were restricted by boat size and operational abilities we did not use the largest collectors. It is possible that other designs might prove more economical to utilize.

An example of a possible alternative design could be based on the long-line concept. A long line arrangement was suggested as a way of attaching and then handling for checking, a series of "Tasmanian" box (Mills) collectors.

Alternatively, collector tassels could be manufactured in a way similar to the turf produced and laid for new lawns. Continuous, or long lengths of an artificial tassel turf could be set as a long line within the shallow reef complexes. With the appropriate boat and handling equipment (such as a shrimp sorting tray), the "turf" could be hauled aboard, the pueruli shaken free, and the "net" re set over the stern of the vessel.

Reducing the cost of constructing collectors is one of the biggest issues facing commercial operators. Tasmania collector trials showed that *J. edwardsii* pueruli will settle on a wide range of substrata. If individual commercial operators have access to a cheap source of material that they believe could be suitable, it is well worth conducting their own trials. Mesh cages as used in Mills collectors can be adapted to contain a wide range of substrata.

7. Benefits

1. The results of these studies provide a strong basis for understanding the effects of possible removals of pueruli and post pueruli from the wild population of the western rock lobster.

Clearly removal of these early life history stages will have minimal effects on the wild harvest, except if extremely large numbers (such as millions) were removed from particular areas.

It is uncertain if an aquaculture industry, based on grow-out of pueruli, will develop. However, if it does occur, there would be benefits to the State through economic and employment opportunities that would be the anticipated outcome of any new aquaculture component to the industry.

2. The project reaffirmed the very high mortality rates that are experienced by juvenile lobsters between settlement and entry into the commercial fishery. More than those though, results from the project strongly suggest that the high mortality rates were experienced in the first year after settlement.

3. The project enabled the trialling of a range of equipment and methods for catching pueruli. As a result of this a protocol has been developed which will assist future operators who may wish to harvest large numbers of pueruli for ongrowing.

8. Further developments

This project has been instrumental in developing an appreciation by the commercial fishing industry and managers of the resource, that enormous potential benefits may be gained by improving the survival of pueruli and post pueruli in the first year after their settlement. This realization has formed the basis of a new FRDC (2002/045) funding proposal that has been successful for funding from 2002/03 onwards, titled 'Assessing the possibilities for enhancing the natural settlement of western rock lobster.' A second project "Establishing post-pueruli grow-out data for western rock lobsters to access economic viability" has been submitted for consideration for funding in 2003.

The project has also shown that the potential exists to harvest large numbers of pueruli and post pueruli with the collectors that have been trialled by the project, and that adjustments can be made (again, using project outcomes) to make harvesting of pueruli and post pueruli biologically neutral. This has resulted in another proposal being successful for consideration for funding from 2002/03 onwards, titled 'Determining optimal density and refuge requirements for culturing western rock lobster in flow through tanks.'

9. Conclusions

This project was undertaken in four parts. In the first, a study examined the impact of possible puerulus exploitation on the future catches in the wild fishery for the western rock lobster in Western Australia, and determined management measures which might be required to maintain 'biological neutrality'. A primary aim of management to maintain sustainability of the Western Rock Lobster Fishery is to maintain the reproductive capacity of the breeding stock at a level sufficient to replenish itself. Biological neutrality is in this context, the level of catch that would be needed to be forgone to compensate the reproductive capacity of the breeding stock if pueruli were removed for aquaculture.

The impact of puerulus removals of *Panulirus cygnus* in the 29°– 30° region on subsequent catch was estimated to be minimal except in the case of removal of very large numbers of pueruli. It is possible to counter these losses by effort reduction, and a set of tables allowing the calculation of these reductions has been provided.

In the second part of this project, methods were investigated to catch large numbers of pueruli. This work suggested that the pueruli of *P. cygnus* will be easiest to catch near the shore, and in selected locations with fringing reefs.

A number of different puerulus collector tests were undertaken for *P. cygnus*, these included (i) modified western rock lobster sandwich collectors at different depths and distances offshore, (ii) different collector designs, (iii) the effect of collector size, and (iv) the effect of frequency of servicing the collectors on catch. The only catches recorded in the onshore-offshore trials were on gear set at the inshore site (depths <5 m). Published data from the 1970s on the effect on catches of collector arrays and locations were reexamined with a general linear model. The analysis revealed marginally significant corner and layer effects, carry-over effects, and square-of-time effects. Five collector designs were therefore set in the shallows, two of which had replicates of three different sizes, and were checked over four lunar months during peak settlement. Sandwich collectors had significantly better catch rates than others ($P < 0.001$), and settlement rates were highly correlated with collector dimensions ($r = 0.72$). Daily servicing for seven days around the time of new moon, yielded catches 170% higher than those from a single monthly servicing ($P < 0.001$). Results indicate that tests for collectors must take into account corner, carry-over, neighbour, and layer effects and that to do so they must be set out in an array and repositioned after each sampling.

Other pueruli harvesting methods were trialled for *P. cygnus*. Neither fixed, pump or mid-water trawling proved to be effective methods of catching pueruli in quantity. Mid-water trawling was the most effective of the three methods and tens of pueruli were caught in inshore areas between the Abrolhos Islands and the coast over four nights when this method was trialled.

In the third part of the project the effect of collector position on localized pueruli catch rates of *P. cygnus* was tested at Shark Bay and Seven Mile Beach. Pueruli collectors set along a 3 km stretch of coastline at Seven Mile Beach did not show uniform linear trend in variation in catch rates in a longshore direction (P>0.14), but neighbourhood effects were shown to exist between individual collectors (p=0.02). Some of the longshore collector sites tended to consistently perform better than others, indicating that in addition to the macro environmental factors that influence puerli collector catch rates, there are likely to also be very localized affects.

The fourth part of this project focused on southern rock lobster (*Jasus edwardsii*) and was carried out in Hobart, Tasmania, by the Tasmanian Aquaculture and Fisheries Institute (TAFI). Sandwich collectors, previously thought to be unsuitable for *J. edwardsii*, were shown in this study to achieve good catch rates when deployed in an alternative fashion (on the seafloor versus at the surface). For the considerable advantages of sandwich type collectors to be realised, a cost-effective method of manufacture will need to be devised. The use of midwater longlines for deploying collectors proved unsuitable, with low catch rates. Use and rigging methods for bottom-set longlines will require further investigation.

Some pueruli of *J. edwardsii* emigrate from collectors after settlement and yield was shown to be greatest when the collectors were serviced at intervals of one week or less during peak settlement periods. Pueruli were lost during the hauling of collectors from the seafloor to the boat, with some escaping whilst hauling to the surface and others being washed from collectors as they were hauled clear of the surface. The use of a scoop net to lift collectors into the boat would go some way towards reducing this loss, and avoids the complication and expense of bagging collectors on the seafloor.

Although it is unlikely that the catch of *J. edwardsii* pueruli per collector will increase substantially with alternative collector types, collection cost per puerulus can be significantly reduced. Thus it would be economically viable to deploy greater numbers of collectors, resulting in an increased total puerulus catch. It will be possible to achieve cost reductions through the construction of cheaper collectors, increased ease of deployment and servicing, and increased retention of puerulus without the need for bagging or dip-netting.

Commercial collection of southern rock lobster pueruli for aquaculture has already commenced in Tasmania, and the Rock Lobster Industry Advisory Committee in Western Australia stated in March 2001, that the project paves the way for a small scale commercial pilot operation collecting puerulus from the northern zone of the fishery for grow out (the on-growing of pueruli to a marketable sized lobster).

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12. Appendices

APPENDIX 1. INTELLECTUAL PROPERTY

There is no identifiable intellectual property arising from the project.

APPENDIX 2. PAPERS PRODUCED

The sandwich collector, developed for commercial-scale harvesting of western rock lobster pueruli.

From: Mark Rossbach, Bruce Phillips and Roy Melville-Smith. **The Lobster Newsletter" Volume 14, Number 1,July 2001**. *Editor: J.Booth C/o NIWA PO Box 14-901, Kilbirnie, Wellington, New Zealand.*

There is increasing interest worldwide in the commercial potential for on-growing juvenile spiny (rock) lobsters. In 1998, Fisheries Western Australia commenced a project, funded by the Fisheries Research and Development Corporation (FRDC) and managed by the Rock Lobster Enhancement and Aquaculture Subprogram, to examine the effect of harvesting large numbers of pueruli of the western rock lobster (*Panulirus cygnus*) on the wild fishery, and to develop large-scale harvesting techniques. We found that one type of collector stood out from all the others; this article describes this collector, its construction, deployment, method of servicing, and more. (See Phillips *et al*. (in press) for descriptions of all the collectors tried, and their catch rates.)

Figure 1. Sandwich collector.

The sandwich collector (Figure 1) is a robust, relatively inexpensive (approximately $AU120) puerulus collector. It is based on the seaweed-type collector used by Montgomery and Craig (1996), that itself based on the Phillips collector (Phillips 1972). It consists of two rectangular, 4.5 mm thick sheets of grey industrial PVC (615 x 350 mm), instead of the three sheets used in the Phillips collector. Glued to the outer face of each sheet is a thin layer of woven polypropylene material. The tassels consist of polyethylene split fibre 125 tex (Kinnears Pty Ltd, Victoria, Australia) which comes in 1.5 m hanks weighing about 1 kg. Each hank is cut into 18 equal length tassels. Each tassel is bound tightly around its midpoint with a 20 cm strand of monel wire, and then attached to the PVC sheet by a 50 cm plastic tie passed through a hole in the sheet. A total of 25 evenly spaced tassels are used on each PVC sheet.

Two such sheets, secured back-to-back, make up the sandwich collector. We use two pieces of jarrah (47 mm x 45 mm x 38 mm), a hard wood grown in Western Australia, and stainless steel bolts to brace and secure the two PVC sheets (Figure 2).

Figure 2. Internal side of the sandwich collector.

Two floats are attached to the jarrah braces at the top of the collector, while a bridle near the base secures the collector to the mooring block. The braces also allow a shaft to be inserted into the collector so that it can be spun when being serviced. Figure 3 shows the spinning shaft position in relation to the PVC sheets and braces.

Figure 3. Location of spinning shaft and spinning tub and holding brackets.

The floats are on short leads so as to avoid tangling the tassels. We use a figure eight knot to attach the floats, a knot that allows the floats to be easily removed when the collector is serviced.

The main difference between the Montgomery and Craig (1996) collector and the sandwich collector is that theirs has a fixed aluminum center bar to which the floats and sheets are attached. We thought this cumbersome to use on our small research craft and it also made the collector more expensive. Furthermore, because we can remove our floats and use the one spinning shaft for all collectors, the size of the unit is minimized and we can service collectors more rapidly because there is no need to align the shaft to insert a pin before spinning the collector.

We use a 40 kg concrete block to moor each collector. About 1.5 m of 12 mm poly rope runs from the bridle at the base of the collector via a swivel to x m of 12 mm galvanised chain, which is in turn shackled to the mooring block. The amount of mooring chain used is generally about twice the water depth. Collectors set in this manner survived severe storms throughout last winter.

Recently we have had problems with the jarrah braces being attacked by shipworm (bivalve family Teredinidae), probably *Teredo navalis*. We need to look at chemical treatments to resolve this problem.

The collectors are positioned to float just below the surface and must be conditioned for at least two months. Our sampling was carried out over full moon. The collector is grappled from a small boat, pulled alongside and lifted onboard – which requires two people because of the weight. The floats and mooring bridle are then removed before the collector is serviced.

The spinning shaft slides into the central holes in the jarrah braces (Figure 3). The whole unit is then placed inside a large tub (Figure 4) with a plastic cover and the collector rotated both clockwise and counter-clockwise 20 times. For large-scale operations a device with an electric motor, like in a chicken rotisserie, would speed up servicing. The sample obtained is then poured into a sieve, sorted and the pueruli counted.

Figure 4. Spinning tub for sampling collectors.

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Testing collector designs for commercial harvesting of western rock lobster (*Panulirus cygnus*) puerulus

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Abstract. We have *(i)* tested modified western rock lobster sandwich collectors at different depths and distances offshore *(ii)* tested different collector designs *(iii)* examined the effect of collector size, and *(iv)* tested the effect of frequency of servicing the collectors. The only catches recorded in the onshore-offshore trials were on gear set at the inshore site (depths <5 m). Published data from the 1970s on the effect on catches of collector arrays and locations were reexamined with a general linear model. The analysis revealed marginally significant corner and layer effects, carry-over effects, and square-of-time effects. Five collector designs were therefore set in the shallows, two of which had replicates of three different sizes, and were checked over four lunar months during peak settlement. Sandwich collectors had significantly better catch rates than others (P <0.001), and settlement rates were highly correlated with collector dimensions (r = 0.72). Daily servicing for seven days around the time of new moon yielded catches 170% higher than those from a single monthly servicing (P <0.001). Results indicate that tests for collectors must take into account corner, carry-over, neighbour, and layer effects and that to do so they must be set out in an array and repositioned after each sampling.

Introduction

The high dollar value of rock lobsters has made them an interesting prospect for aquaculture and has stimulated numerous reviews (e.g. van Olst *et al*. 1980; Provenzano 1985; Kittaka and Booth 2000). A major stumbling block in realizing the aquaculture potential of these animals has been the difficulties of rearing the larvae through their long and complicated pelagic stages. Although some species have been successfully reared through their larval life (Kittaka 2000), the production of large numbers of postlarvae has not yet been possible, and successful commercial application seems some years away.

In contrast, the postlarvae are relatively easy to rear, and numerous authors have reported on the potential for their on-growing to marketable size (e.g. Tholasilingam and Rangarajan 1986; Phillips 1988 1997; Meagher 1994; Kittaka and Booth 2000). Good markets, particularly in Japan, exist for small lobsters, and it is this market that would initially be the target of those contemplating the harvesting and culturing of spiny lobster pueruli.

A number of different types of collectors have been used to catch settling pueruli (see review by Phillips and Booth 1994), but none was designed to catch large numbers. The present paper reports initial studies developed to catch large numbers of pueruli for aquaculture or enhancement purposes.

Materials and methods

Onshore/offshore trials

Optimal depths and distances offshore for the collection of pueruli with tassel-style collectors based on the 'seaweed' collector (Montgomery and Craig 1994), described more fully below as 'sandwich' collectors, were tested during 1998.

Sandwich collectors (each providing a total collection area of 0.43 $m^{2)}$ were attached in tandem to dropper ropes at various depth intervals along an offshore transect west of Cervantes, Western Australia (Fig. 1), over two lunar months during October and November 1998. The collectors were initially positioned in waters approximately 3, 10, 36–40, 60, and 120 m deep (Fig. 1). After one month the collectors set at 10 m had to be repositioned to 20 m because of gear damage caused by surge and swell associated with the shallows. The inshore station (near Cervantes) was approximately half a nautical mile from the beach, and that farthest offshore was approximately 17 nautical miles west of that point.

Lines of collectors were set according to the bottom type and depth profile. The two inshore lines were over hard bottom, but those in the deeper water were over hard reef (36 m), sand/weed (40 m), hard bottom at the top of the drop-off (50 m), and finally silt on the drop-off slope (~120 m). Because of concerns about the buoyancy of the floats and the ability of the anchors to prevent the dropper lines from drifting, each line was limited to supporting a maximum of four sandwich collectors. The four inshore lines were made up of two dropper lines, one with a surface and a bottom collector and the other with a surface and a mid-water collector set at 20 m (Fig. 1). The most inshore station

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APPENDIX 3. STAFF

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Dr Roy Melville-Smith	Co-Investigator	*
Dr Nick Caputi	Research Supervisor Invertebrates	#
Dr Henry Cheng	Senior Research Scientist	#
Mr Mark Rossbach	Senior Technical Officer	*
Mr Adrian Thomson	Statistical Officer	*
Casual Staff	Casual Assistants from Dongara.	*
Mr David Mills	T.A.F.I.	
Dr Brad Crear	T.A.F.I.	

* Staff employed for parts of the project under FRDC funding.
\# Trained staff who assisted with the project using non-FRDC funds.

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