FINAL REPORT

Growth of Pearl Oysters in the Southern and Northern Areas of the Pearl Oyster Fishery, and Examination of Environmental Influences on Recruitment to the Pearl Oyster Stocks

Anthony Hart
Craig Skepper
Lindsay Joll

Western Australian Marine Research Laboratories
PO Box 20, North Beach, WA 6020, Australia

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95/41	**Growth of Pearl Oysters in the Southern and Northern Areas of the Pearl Oyster Fishery, and Examination of Environmental Influences on Recruitment to the Pearl Oyster Stocks**

PRINCIPAL INVESTIGATOR: Dr Anthony Hart
ADDRESS: Western Australian Marine Research Laboratories
PO Box 20, North Beach, WA, 6020
Telephone: 08 9246 8444 Fax: 08 94473062
e-mail: ahart@fish.wa.gov.au

OBJECTIVES:

1. To determine growth rates of pearl oysters in the Lacepede Channel and Exmouth Gulf areas of the WA pearl oyster fishery.
2. To utilize the existing and new knowledge of time lags between spatfall and recruitment to the fishery and the period of vulnerability to fishing to carry out analyses of possible environmental influences on recruitment.

Non-technical Summary

The pearling industry is Australia's most valuable aquaculture industry, generating approximately $187 million in 1997. However, the silver-lipped pearl oyster (*Pinctada maxima*) used to culture South Sea pearls is derived principally from stocks of wild shell. Fisheries Western Australia has been conducting a variety of studies on wild stocks of pearl oysters since 1989 to provide the knowledge-base necessary to evaluate their status and set annual quota levels. Most of these studies have focused on stocks in the 80 Mile Beach and Lacepede Channel areas, which together provide about 80% of the annual wild stock quota. Catch rates in these areas increased dramatically during 1992 - 1995, with industry observations suggesting a strong pulse of recruitment which appeared to extend over a number of years. This study investigated environmental and catch rate data over the past 19 years so as to provide a better understanding of possible environmental influences on pearl oyster recruitment. However, in order to determine the appropriate time lags between environmental effects at the time of spat settlement, juvenile stages, and recruitment to the fishery, it was necessary to further extend the existing database on growth to other areas of the fishery.

Growth parameters of *P. maxima* were determined for the Lacepede Channel and Exmouth Gulf stocks over 2 years (1996-1998). This data was used to calculate the time lag between settlement and recruitment into the fishery for each area. There is currently no recruitment index *per se* for the pearl oyster fishery, as exists for other invertebrate fisheries in WA, e.g. the western rock lobster fishery (Caputi et al. 1998). The only long term data set for the fishery which may reflect recruitment is the historical catch and effort data (ie. culture age oysters/diver hour). Therefore it was necessary to first establish the usefulness of fishery catch rates as a recruitment indicator by correlating catch rates with piggyback spat abundance data obtained during a previous study (Joll, 1996). The abundance of the various size classes of

piggyback spat (spat which have settled onto adult [legal size] shells) is hypothesised to reflect both settlement strength and juvenile survival.

The growth studies indicate that pearl oysters are in their third year of life when they enter the fishery at both the Lacepede Islands and Exmouth Gulf. The data suggest that pearl oysters from the Lacepede Islands stock reach legal minimum length (LML) approximately 6 months before oysters from Exmouth Gulf. However, pearl oysters from Exmouth Gulf grow at a slower rate and remain in the exploited size range for 1 year longer than those from the Lacepedes. The growth rate in the Lacepedes is similar to that found in Joll (1996) for oysters on the central fishing grounds off the 80 Mile Beach (Zone 2 of the fishery). Although there are about 3 age classes in the culture shell catch rates, most of the catch is expected to come from the first age class in areas of high exploitation. Therefore the appropriate time lags relating settlement strength (and the corresponding environmental conditions) to recruitment as measured by fishery catch rates are 2 - 3 years.

Positive correlations were found between piggyback spat collection rates and fishery catch rates during the 5 year period (4 years in zone 3) when data on recruitment was available. In zone 2, spat collection rates were a good predictor of fishery catch rates at both 1 and 2 years lag. Because of the limited number of data points available these results are still very preliminary, however, they did enable us to conclude that catch rates were a sufficiently reasonable representation of recruitment to enable them to be used as a proxy recruitment index when examining the longer term question of environmental influences on the fishery.

Sixty nine percent (69%) of the variability in raw annual pearl shell catch rates during the years 1980 - 1998 in Zone 2 was explained by 3 environmental variables at a 2 year time lag. The variables were sea surface temperature (SST) in December, rainfall in December (as an index of freshwater input or monsoon season strength), and the annual Southern Oscillation Index (SOI). A 2 year time lag indicates the environmental effect occurs during the spat phase of the life cycle. Of these variables, rainfall in December and SOI had a significant influence on the variation in catch rates. Rainfall was deemed the most important, and was correlated positively with catch rates ($r = 0.58$). SOI was negatively correlated with catch rates ($r = -0.56$), suggesting that recruitment was enhanced during El Nino years. Similar results were seen in Zone 3. In this zone, 66% of the variability in catch rates was explained by December sea surface temperatures, and the SOI two years previously. SST had a significantly positive influence on catch rates, and SOI was negatively correlated with catch rates. These analyses allow us to generate an hypothesis regarding factors influencing recruitment which need to be tested as more data becomes available.

The results clearly suggest an environmental influence corresponding with El Nino conditions may be implicated in high recruitment events, as indicated by spat collection data and catch rates in two zones of the fishery. It needs to be noted however, that evidence for this relationship arises from one major ‘spike’ in catch rates, which occurred during the extended El Nino of the early 1990’s and at the same time GPS technology was being adopted by industry. The influence of GPS technology on fishing efficiency cannot be underestimated, as demonstrated in the northern prawn fishery (Robins et al. in press). That study found that, after a 3 year period, vessels with GPS plotters increased their fishing efficiency by 12%. In the pearl oyster fishery, early evidence indicates that catch rates have stabilised at around 30 shells per hour, which is approximately 30% higher than historical averages prior to the 3 year period of high catch rates. Our hypothesis is that this is due, at least partly, to an increase in fishing efficiency.

A number of recommendations on future research have arisen from this study. These are:

- The "piggyback" spat settlement program be restarted to obtain a reliable fishery independent measure of future year-class strength.
- The usefulness of fishery catch rates would be enhanced if size frequency data were available for the commercial catch (a research program is being proposed to obtain this data).
- The influence of environmental variables on recruitment needs to be incorporated into annual stock assessment in the WA Pearl Oyster Fishery.
- A standardised catch rate index which incorporates both fleet dynamics and historical changes in technology should be developed for the WA Pearl Oyster Fishery. This would provide better data against which to examine environmental influences, particularly if the catch rate data could be examined by size.
- The relationship between "piggyback" spat settlement, environmental effects and recruitment to the fishery which.can be used to forecast increases/decreases in abundance should be developed. This enables changes to quota to be forecast to allow forward planning in pearl seeding and farm operations.

KEYWORDS: *Pinctada maxima*, pearl oyster fishery, growth, environmental influences, recruitment

1. Background

The pearling industry is Australia's most valuable aquaculture industry, generating approximately $187 million in 1997 (source: ABARE 1997). The oysters used to culture pearls are derived almost entirely from wild stock shell, rather than hatchery produced stock as occurs in other major pearling industries. Fisheries WA has been conducting a variety of studies on wild stocks of pearl oysters since 1989 to provide the knowledge-base necessary to evaluate their status and set quotas. Most of these studies have focused on stocks in the 80 Mile Beach and Lacepede Channel areas, which provide about 80% of the annual wild stock quota. Catch rates in these areas have shown a major upswing in recent years, with the 1993 catch rate being 70% higher than the 10 year average (1983-1992). The increases in catch rate are believed to arise primarily from a major increase in recruitment, rather than any increases in diver or vessel efficiency. The recent period over which catch rates have increased corresponds with a prolonged El Nino lasting 4 years. Examination and analysis of environmental and catch data over past years may provide a better understanding of possible environmental influences on pearl oyster recruitment. However, in order to determine the appropriate time lags between environmental effects at the time of recruitment as spat, and recruitment to the fishery, it was necessary to further develop an understanding of growth in other areas of the fishery.

2. Need

A large database on growth has been developed for populations in the 80 Mile Beach area and is in the process of analysis. It indicates that pearl oysters are in their third year of life when they become vulnerable to fishing, and that they grow through the size classes which are exposed to fishing mortality for a further 3 years. However, there is a concern that the growth data determined for 80 Mile Beach may not be applicable to the other main areas of the fishery (Lacepede Channel and Exmouth Gulf). Data on modal shifts of juveniles caught in the spat rate studies (FRDC 92/147) suggest that growth in the Lacepede Channel area is much faster than at 80 Mile Beach, but independent confirmation of this through tagging studies was required. There are no data on growth rates of pearl oysters in the Exmouth Gulf area, although being near the southern limit of the species' distribution, it is likely that growth rates at this location will be slower than at 80 Mile Beach. However, since the allocation of additional quota in the southern sector of the fishery (Zone 1), Exmouth Gulf has assumed a high level of importance in providing pearl oysters for the Zone 1 fishery (85% - 1993, 75% - 1994), and it is important that data are obtained for this locality. In order to be able to provide the correct time frames for any examination of possible environmental effects on recruitment of pearl oysters, it is important that there is a sound understanding of the time from spatfall to recruitment into the fishery in each sector of the fishery and the corresponding periods of exposure to fishing mortality in each sector.

3. Objectives

1. To determine growth rates of pearl oysters in the Lacepede Channel and Exmouth Gulf areas of the WA pearl oyster fishery.
2. To utilize the existing and new knowledge of time lags between spatfall and recruitment to the fishery and the period of vulnerability to fishing to carry out analyses of possible environmental influences on recruitment

4. Methods

4.1. Growth Studies

Sites: Tag - recapture experiments were established at the northern (Lacepede Channel) and southern (Exmouth Gulf) limits of distribution of commercial densities of the silverlip pearl oyster (*Pinctada maxima*) in Western Australia (Fig 1). Previous studies had already established growth from the main sector (80 Mile Beach) of the pearl oyster fishery (Joll, 1994).

Tag Lines : At both sites it was necessary to established fixed areas for the placement of tagged shell for the duration of the experiment, as this greatly increases the potential for tag recaptures. The Lacepede Channel area was situated at 17° 01’ 20’’ N, and 112° 15’ 35’’ E. It consisted of an area (~500m^2) of suitable pearl oyster substrate in approximately 18 metres depth, marked on the seabed by a series of lengths of chain and rope (175m in total length), anchored at each end by a suitable mooring (‘tag lines’). Both moorings were marked with a set of surface buoys.

The Exmouth Gulf area was situated at 22° 26’ 09’’ N, and 114° 10’ 36’’ E. It consisted of a rectangular area (60m x 300m) of pearl oyster habitat in approximately 5 metres depth, marked at each end by a mooring with surface buoys attached.

Initial Tagging, Measurement And Release : Oysters intended for tagging were collected by research divers and from undersize and oversize ‘discard’ shell from commercial pearling vessels. Each shell was measured for dorso-ventral length (DVL), anterio-posterior length, hinge length, shell width and heel depth using standard calipers and measuring boards. A numbered plastic polyethylene tag was secured on each valve of the pearl oyster using cyano-acrylate glue. The oysters were then transferred to holding tubs prior to release.

At the Lacepede Channel site, each tagged pearl oyster was individually placed on the seabed within 15m either side of the tag line by research divers swimming along the line during periods of tide change (slack water). A total of 1670 pearl oysters were tagged, measured and released at the Lacepede Channel site in February 1996.

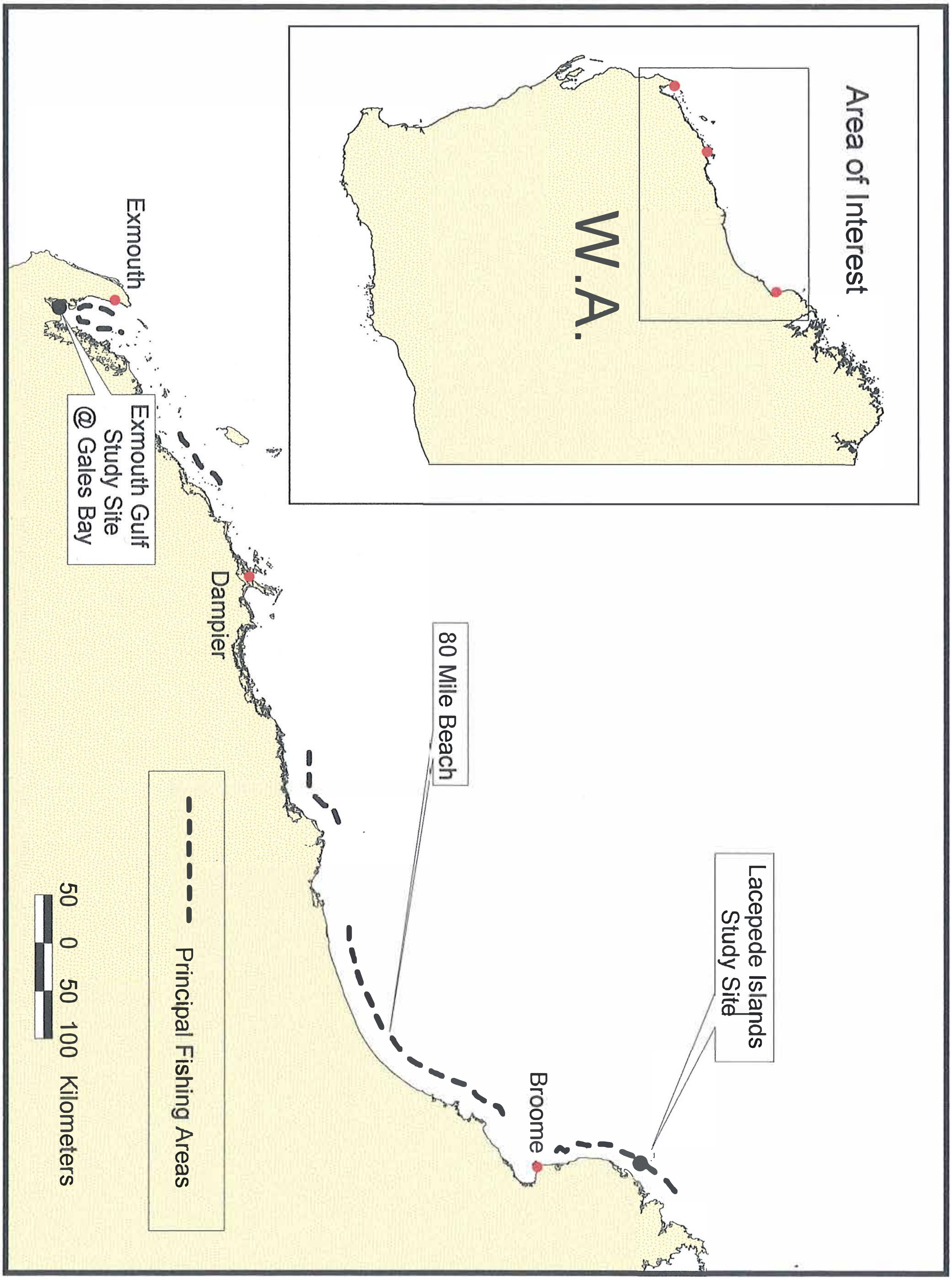

Figure 1. Map of the W.A. Pearl Oyster Fishery and the tag sites for growth studies

At the Exmouth Gulf site a drift diving system similar to that used in the pearl diving industry was employed. Research divers were towed by a slowly moving vessel using a system of weights and ropes to allow divers to maintain contact with the seabed. Using this system, pearl oysters were both collected and later released by research divers within the study area. A total of 964 pearl oysters were tagged, measured and released at the Exmouth Gulf site in June 1996.

Recapture : Recaptures and re-measurement of tagged pearl oysters at the Lacepede Channel site were made after 1 and 2 years at liberty by research divers retrieving shell while swimming along the tag line. A total of 293 recaptures were made in 1997, and 84 recaptures in 1998. An additional 122 pearl oysters were tagged during the 1997 recapture trip.

The drift diving system described earlier was used for the recapture of tagged pearl oysters after 1 and 2 years at liberty at the Exmouth Gulf site. A total of 275 recaptures were made in June 1997, and 212 recaptures in June 1998. In 1997 an additional 273 newly tagged pearl oysters were added to the experiment.

4.1.1. Data analysis for growth

Faben's reformulation of the von Bertanffy growth curve was used to estimate the growth parameters K and L_∞ of the von Bertalanffy growth curve. The von Bertalanfy growth curve is as follows:

$$L(t) = L_\infty\left(1 - e^{-K(t-t_0)}\right)$$

where L_∞ is the expected maximum size, K is the growth rate $L(t)$ is the expected length at time t, and t_0 is the initial age at size zero.

If the age is unknown and the data come from capture-recapture experiments, as is the case for pearl oysters, Fabens method is used to estimate the growth parameters.

$$\Delta l_i = \left(L_\infty - l_i\right)\left(1 - e^{-K\Delta t_i}\right) + \varepsilon_i$$

where ε_i ~ NID $(0,\sigma^2)$, Δl_i is the change in length from recapture of the ith animal, Δt_i is the change in time from recapture of the ith animal. Using non-linear regression techniques, K and L_∞ were estimated.

Growth parameters were determined for 2 years growth (1996-1998), and yearly growth for 1996-1997, and 1997-1998. This data was used to calculate the time lag between settlement, and recruitment into the fishery for the two different areas.

4.2. Environmental Influences on Recruitment

The examination of environmental influences on recruitment of pearl oysters is contingent on a number of factors. Firstly, there is currently no recruitment index *per se* for the pearl oyster fishery, as exists for other invertebrate fisheries in WA, e.g. the western rock lobster fishery and Shark Bay scallop fishery (Caputi et al. 1998). The only long term data for the fishery is historical catch and effort data. Therefore it was necessary to establish the usefulness of fishery catch rates as a recruitment indicator. Growth rates provide data for the time lag between settlement of spat and recruitment into the fishery. Catch rates were then compared at the appropriate time lags, with environmental variables.

4.2.1. Fishery catch rates as a recruitment index.

Two previously funded FRDC studies (Joll, 1994; 1996) investigated recruitment measurement in the WA pearl oyster fishery. These projects identified a potentially useful and cost effective measure of recruitment - the piggyback spat collection rate. Piggyback spat are pearl oyster spat which are attached to adult pearl oysters, presumably as a result of having settled out from the plankton onto the oyster at metamorphosis. The data on spat were collected on commercial vessels during their normal fishing operation. The age classes of these spat are 0+ and/or 1+ and generally range from 20 to 70 mm shell height with 2 size classes apparent for the 80 Mile Beach data (Joll 1996). Although Joll (1996) concluded that spat collection rates from commercial vessels did not appear to provide a useful broadscale index of recruitment, that study lacked the necessary future data on fishery catch rates to compare with the piggyback spat data.

Data on piggyback spat collected in both zone 2 and zone 3 of the fishery during 1991 - 1995 are compared with the fishery catch rates at 1 and 2 year time lags. For example, spat collection rates from 1995 were compared with catch rates from the fishery in 1996 (1 year lag) and 1997 (2 year lag). Pearson's correlation analysis was carried out, however, due to the small number of data points for the piggyback spat index, i.e. 3 - 5 points, any results must be interpreted with caution.

Analyses were carried out for raw and standardised fishery catch rate data, and raw and standardized spat data by zone, grid, and size-class of the piggyback spat. The standardised annual catch rate data were calculated by taking into account the effects of location (10 x 10 mile grids), depth, and neap (time of year) on catch rates in an ANOVA of the catch rates (see Joll 1996).

4.2.2. The effect of environmental factors on recruitment into the pearl oyster fishery

To understand the nature of potential influences of environmental variables on recruitment of pearl oysters, it is necessary to briefly examine the life cycle and breeding times. Animals spawn in October-November, and the larvae spend about 3 weeks in the water column. Hence, settling time is during the months of November and December, which are the beginning of the wet season. Environmental conditions during settlement and in the early juvenile phases are likely to be of crucial importance in the survival of the spat to the fishery.

A range of published environmental variables were compared with fishery catch rates (as an index of recruitment) over a 19 year period spanning 1980 - 1998. In Western Australia, the Leeuwin Current is the dominating influence on the coastal hydrology (Caputi et al., 1998), and it in turn is influenced by the El Nino Southern Oscillation (ENSO) phenomena. A range of other environmental variables also reflect ENSO phenomena, including sea surface temperature (SST), rainfall, sea level height (SLH), and the southern oscillation index (SOI). SST and rainfall at the crucial months of spawning and settlement (November and December) were hypothesised to be critical factors in the survival of larval and settlement stages. SLH at Fremantle can be used as a measure of the strength of the Leeuwin Current, which has been shown to be the dominating influence on many commercially important invertebrate fisheries on the west coast of Australia (Caputi et al. 1998). Annual SOI is a measure of the strength of the El Nino, which in turn exerts a large influence on the Leeuwin Current. These variables were each examined for their influence on catch rates in Zone 2 and Zone 3 at various time lags.

4.2.3 Data analysis

Pearson product-moment correlations between environmental variables and recruitment were initially carried out to determine where significant differences might lie. After this preliminary inspection of the data, a more rigourous analysis was carried out. The influence of environmental variables on recruitment (via catch rates) to the fishery was examined by multiple regression analyses. The explanatory variables in the regression model were sea surface temperature, rainfall, sea level height, and the southern oscillation index. Relative contributions of each variable to explaining total variability in pearl oyster catch rates are summarised by the magnitudes of their Beta values (standardized partial regression coefficients), and partial correlation coefficients. The presence of unacceptable collinearity in the regression models was tested for by the tolerance statistic, which must be greater than 0.1 for each variable in the model (Kleinbaum et al. 1988). This analysis identifies potential environmental variables which explain variation in recruitment to the fishery. This enables us to generate a hypothesis for factors affecting recruitment which will be tested as more data becomes available.

5. Results/Discussion

5.1. Growth Studies

Table 1 summarizes the growth data for Exmouth Gulf and the Lacepede Channel. Initial tagging resulted in 1670 pearl oysters at the Lacepede Channel and 964 pearl oysters at Exmouth Gulf being tagged. At the Lacepede Channel the size-range of pearl oysters tagged was between 30 - 225mm DVL (Fig 2). Oysters tagged at 30-

50mm are interpreted to represent the 0+ age group (Joll, 1996). Oysters tagged were mostly below legal minimum length (120mm), or above 160mm, which is the size at which oysters are no longer taken by the commercial fishery because of their limited usefulness in the production of round pearls. In 1997, 293 pearl oysters were recaptured and measured, and an additional 122 animals were newly tagged and released. A final recapture of 86 animals was made in 1998. Fig 2 and Fig 3 summarise the size-frequency and growth increment data of the animals tagged and recaptured from the Lacepede Channel.

The size-range of pearl oysters tagged in Exmouth Gulf was between 60 - 230mm DVL (Fig 4). Oysters tagged covered most of the adult size range, although again the majority were below legal minimum length (120mm) or above 160mm - the sizes not utilised by the commercial fishery. In 1997, 275 pearl oysters were recaptured and measured, and an additional 273 animals were newly tagged and released. A final recapture of 212 animals was made in 1998. Fig 4 and Fig 5 summarise the size-frequency and growth increment data of the animals tagged and recaptured from Exmouth Gulf.

5.1.1. Growth of **Pinctada maxima** *at the Lacepede Channel.*

The growth parameters, K and L_∞ were 0.31 and 207mm respectively for growth during 1996 - 1997 (Table 1). For 1997 to 1998, K and L_∞ were 0.36 and 193mm respectively. Thus growth seemed faster in the second year, although the difference is marginal. For two years growth data (1996-1998) K and L_∞ were 0.42 and 200mm, however this figure only applies to the size range 100 - 220mm.

Figure 6 summarises the three growth curves obtained for the Lacepede Channel tagged oysters. The ages shown are relative ages as t_0 has been arbitrarily set to zero. According to growth over 1996 - 1998 animals enter the fishery at 2 years of age, and grow through the exploited size class (120-160mm) within two years, so by the age of 4 are no longer exploited. The other growth curves suggest that the animals may be closer to 3 years of age when they enter the fishery, but still only spend 2 years in the exploited phase before growing beyond the size range that is harvested commercially.

Table 1
Summary table for growth analyses

	Lacepede Islands no. of oysters	$L\infty$ (mm)	K	Exmouth Gulf no. of oysters	$L\infty$	K
No. of tagged pearl shell released in 1996	1668			1227		
Recaptured in 1997, 1 years growth	293	207.4	0.306	275	205.4	0.347
No. of new tagged pearl shell released in 1997	122			267		
Recaptured in 1998, 1 years growth	56	193.4	0.355	212	203.9	0.267
Recaptured in 1998, 2 years growth	50	200.0	0.42	140	206.9	0.286

5.1.2 Growth of **Pinctada maxima** *at Exmouth Gulf*

The growth parameters, K and L_∞ were 0.35 and 205mm respectively for growth during 1996 - 1997. For 1997 to 1998, K and L_∞ were 0.27 and 204mm respectively. Thus growth seemed slower in the second year, but the difference is certainly minimal. For two years growth data (1996-1998), K and L_∞ were 0.29 and 207mm, approximately similar to the individual year growth.

Figure 7 summarises the three growth curves obtained for the Exmouth Gulf pearl oysters. Initial growth appears slightly slower in Exmouth Gulf, as animals enter the fishery at about 2.5 to 3 years of age, and take three years to grow through the exploited size range (120-160mm). Pearl oysters are mostly still in the fishery by 5 years of age, and have grown into the protected broodstock size (>160mm) once they reach 6 years of age.

5.1.3. Time lags between settlement and recruitment into the fishery

The growth studies indicate that pearl oysters are in their third year of life when they enter the fishery at both the Lacepede Channel and Exmouth Gulf, with Lacepede Channel pearl oysters showing a similar growth to those from 80 Mile Beach (Joll 1996), reaching LML, on average, 6 months before those in Exmouth Gulf. The data also indicates that pearl oysters in Exmouth Gulf remain in the fishery for 1 year longer than those at the Lacepede Channel. Although there are about 3 age classes in the culture shell catch rates, most of the catch is expected to come from the first age class in areas of high exploitation. This suggests that the appropriate time lags for relating settlement strength (and the corresponding environmental conditions) to recruitment as measured by fishery catch rates are about 2 - 3 years, with the Lacepede Channel and 80 Mile Beach closer to 2 years.

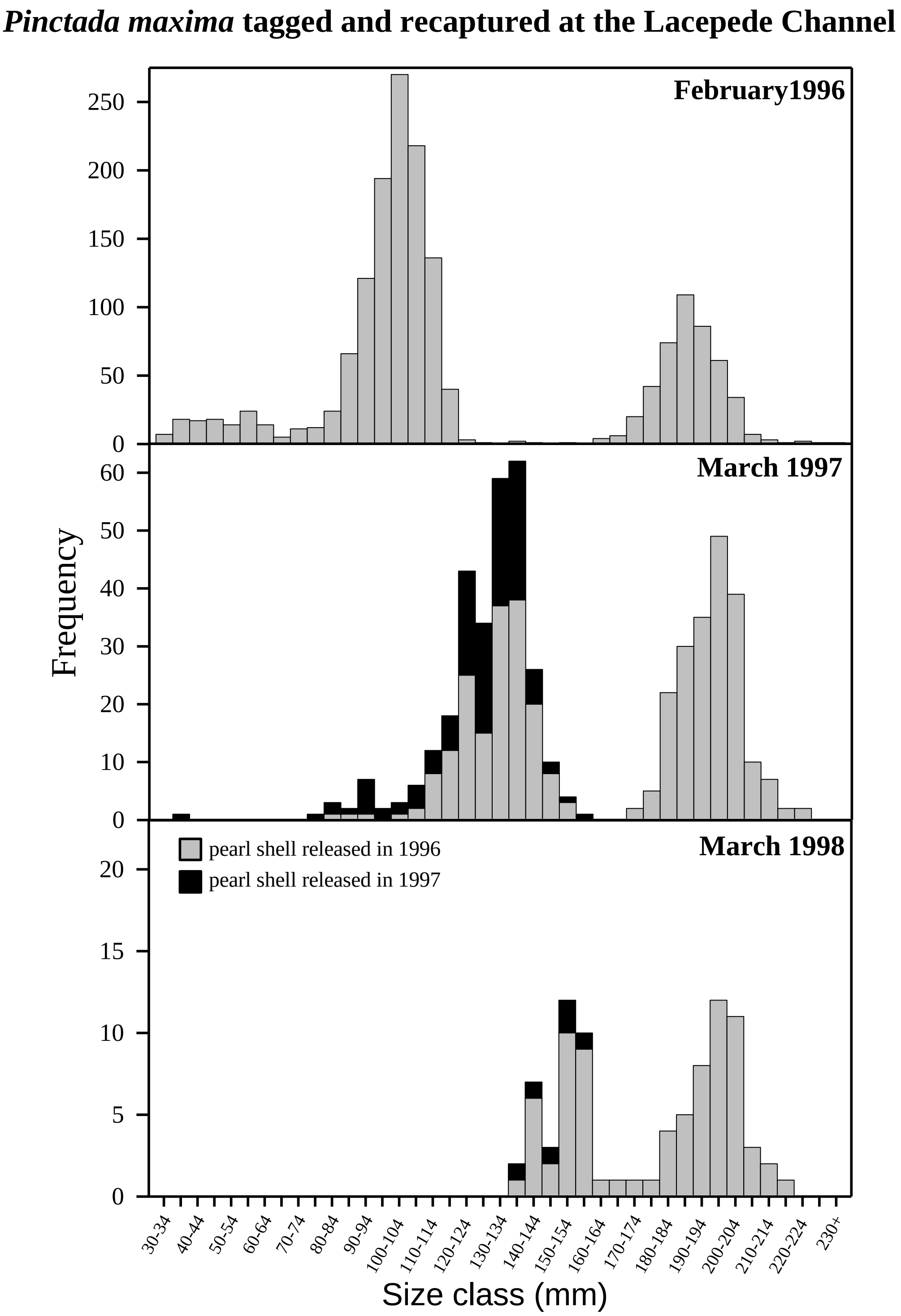

Figure 2. Size frequency of *Pinctada maxima* tagged and recaptured at the Lacepede Channel during this study.

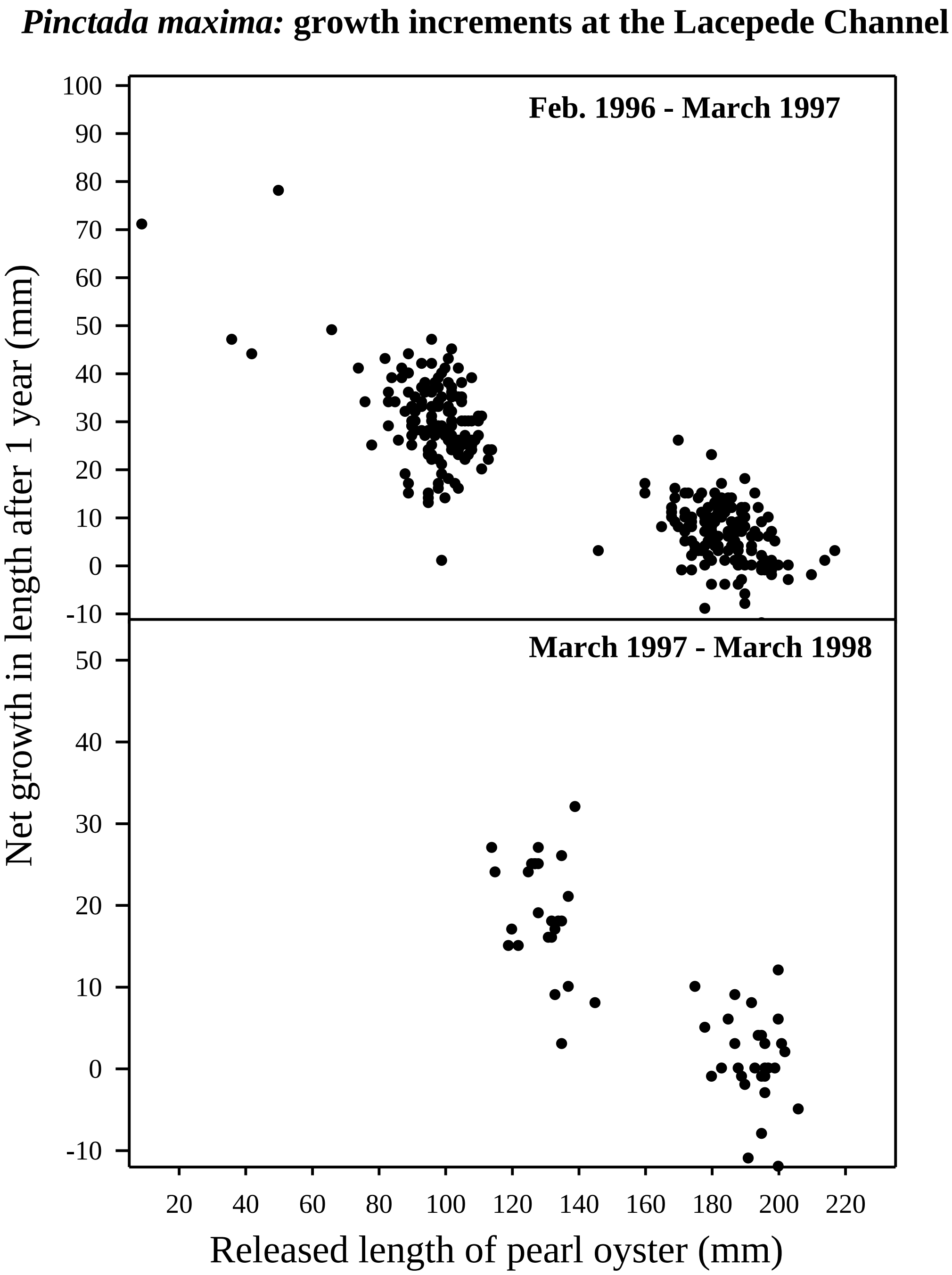

Figure 3. Growth increments and size at release of tagged *Pinctada maxima* recaptured at the Lacepede Channel. Note differences in scales. Outliers removed from analysis.

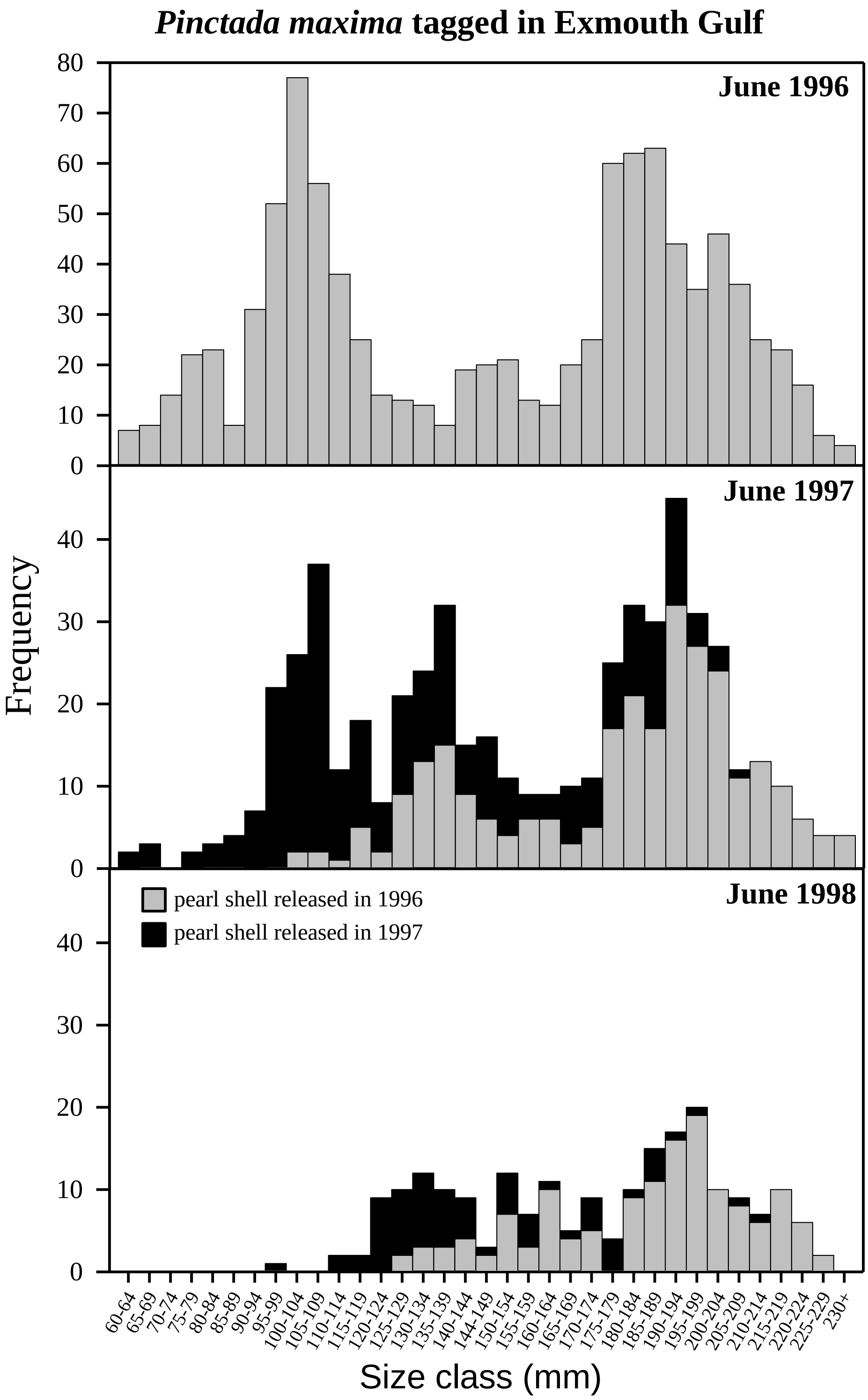

Figure 4. Size frequency of *Pinctada maxima* tagged and recaptured at Exmouth Gulf during this study.

***Pinctada maxima:* growth increments in Exmouth Gulf**

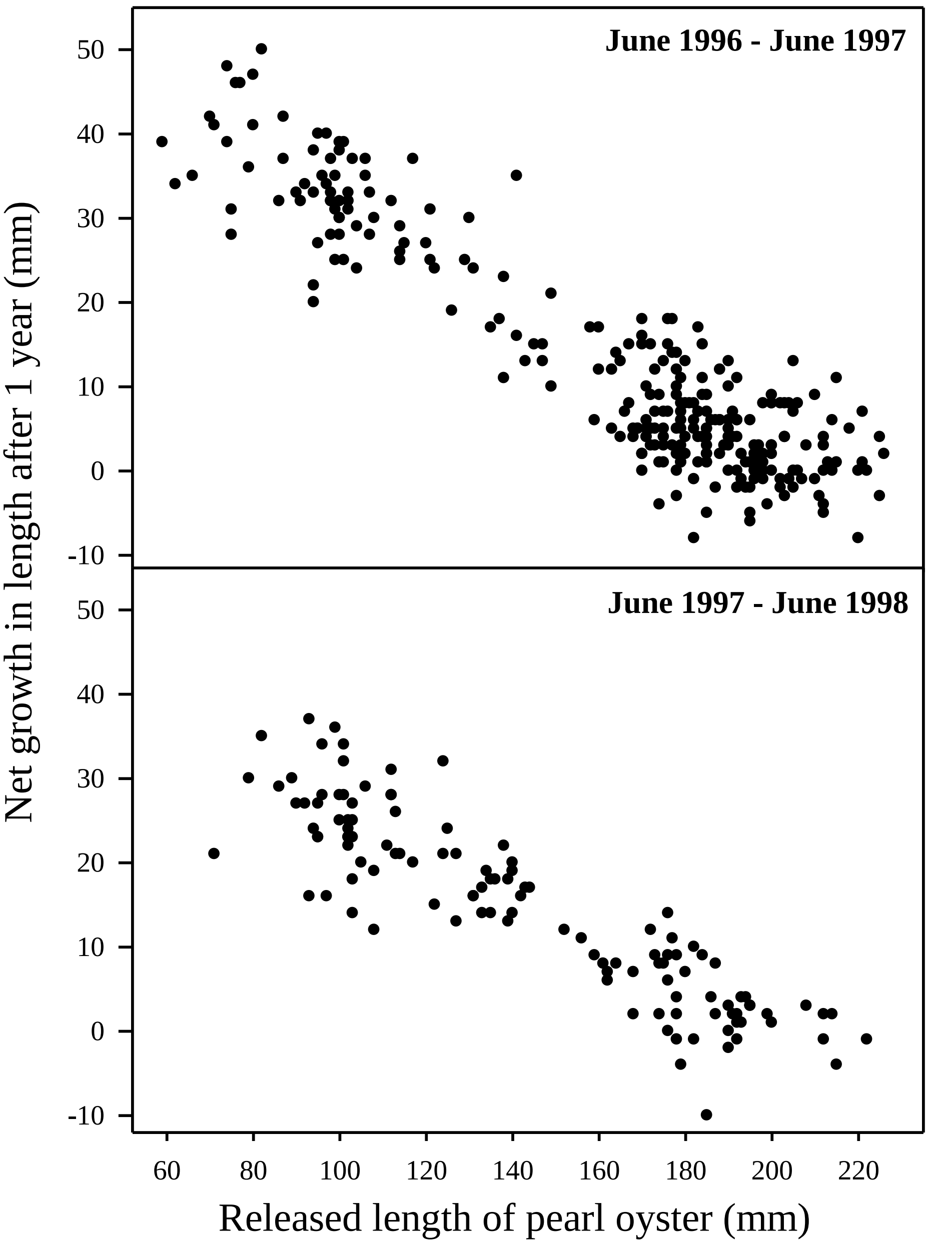

Figure 5. Growth increments and size at release of tagged *Pinctada maxima* recaptured at Exmouth Gulf. Outlier removed from analysis.

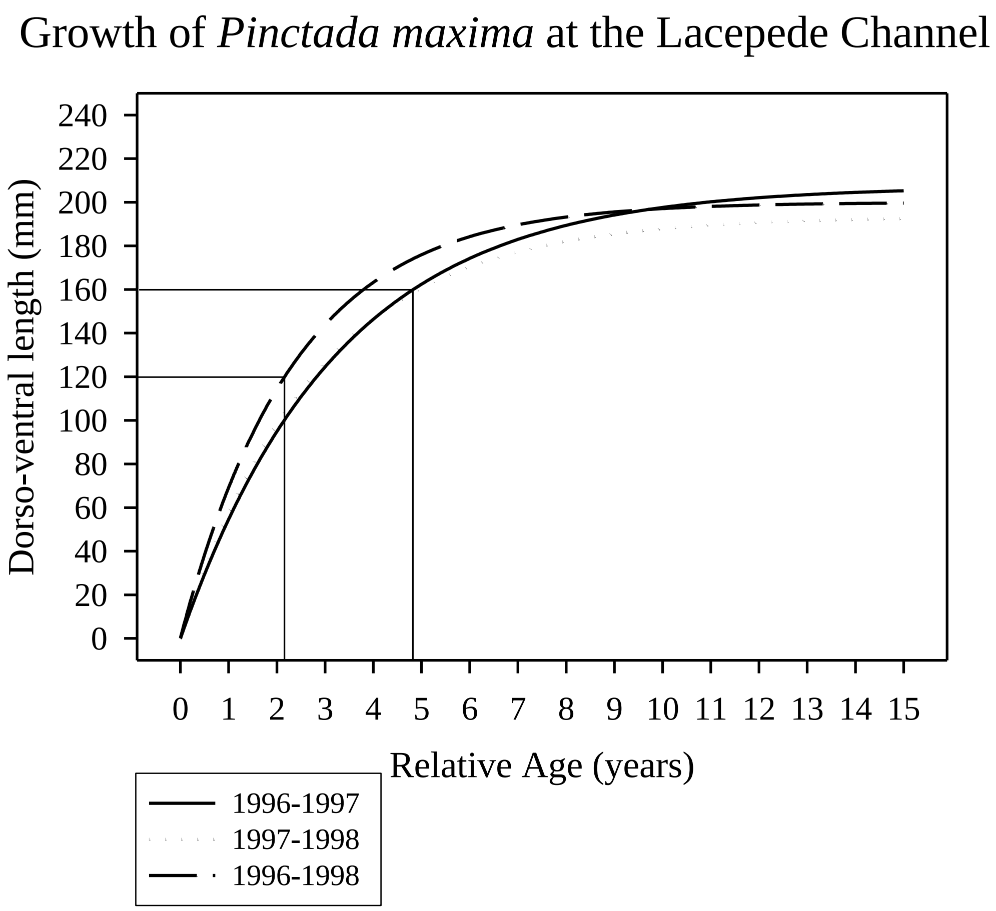

Figure 6. Von Bertalanffy growth curves for *Pinctada maxima* recaptured at the Lacepede Channel. Growth curves for individual years are plotted, and the enclosed areas indicate sizes and ages at which the oysters are commercially harvested. t_0 set to 0.

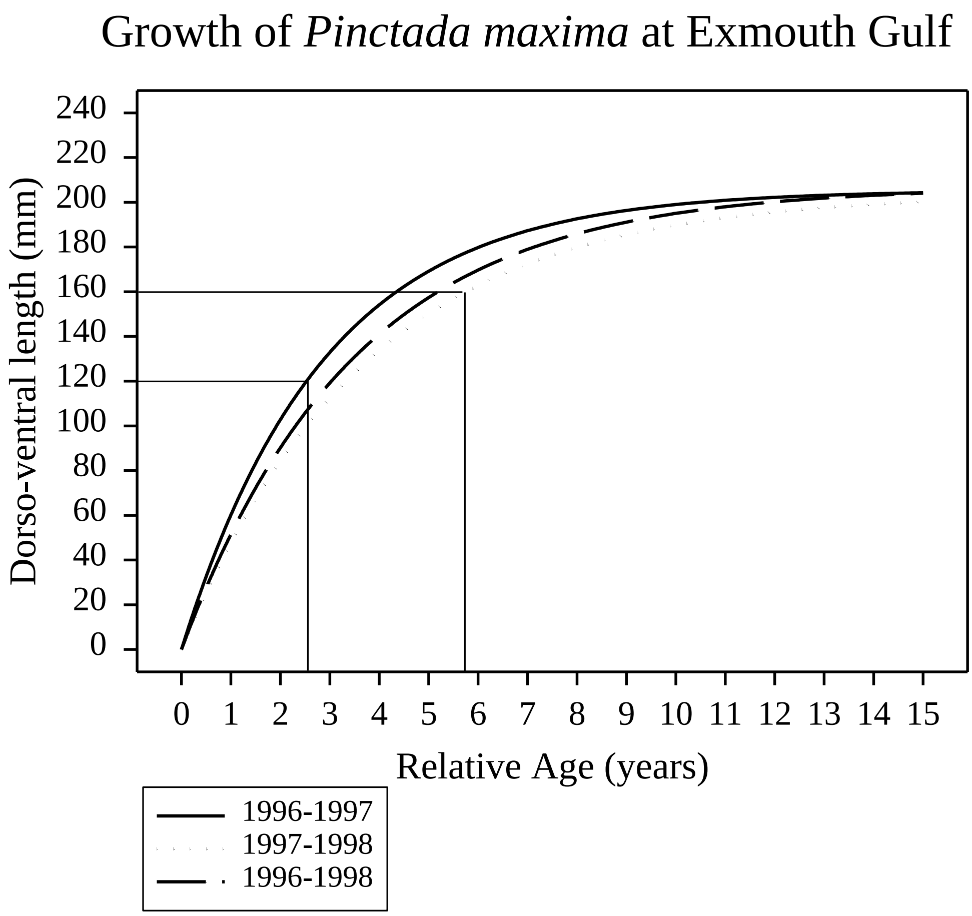

Figure 7. Von Bertalanffy growth curves for *Pinctada maxima* recaptured at Exmouth Gulf. Growth curves for individual years are plotted, and the enclosed areas indicate sizes and ages at which the oysters are commercially harvested. t_0 set to 0.

5.2. Environmental Influences on Recruitment

5.2.1. Catch and effort in the WA Pearl Oyster Fishery

Clear evidence for a possible environmental signal is seen when reviewing the historical catch rate data from WA's pearl oyster fishery (Fig. 8). In the 11 years between 1980 and 1992, catch rates of culture shell oscillated between 20 and 28 shells per diver hour, with a couple of spikes in the mid- and late 80's (Fig 8). Both spikes occurred about 2 years after the ENSO events of 1982-83 and 1986-87. However, between 1992 and 1995 catch rates increased dramatically, up to 41 shells per diver hour, before falling back to around 30 shells per hour in 1997 and 1998. Again, this increase coincided with the longest ENSO event this decade (1991-94).

When the data is divided into Zone 2 and Zone 3 separately, a similar pattern occurs (Fig 9 and 10). The peak in catch rates in 1995 is especially spectacular in Zone 3 (Fig 10). Catch rates peaked at 50 shells per diver hour in 1995 before dropping very quickly back to the 5 year average (approximately 22 shells per diver hour). The existence of these peaks in catch rate, especially when compared against background averages, is evidence in favour of an environmental influence on recruitment of *Pinctada maxima* in WA which is likely to be associated with ENSO events.

5.2.2. Evidence for direct links between catch rate (as an index of) and settlement strength/juvenile abundance.

Results of correlation analyses between piggyback spat data and fishery catch rates are seen in Table 2. In both Zones 2 and 3, very high correlations were observed between piggyback spat collection rates and fishery catch rates. In Zone 2, spat collection rates were significantly positively correlated with fishery catch rates at one and two year lags. However the 1 year lag correlation is biologically unreasonable, as the growth data shows that it is likely to take greater than 1 year for the spat to grow to legal size. The strength of these correlations at the 2 year lag, despite only a few data points, suggests a possible predictive relationship between spat collection rates and fishery catch rates in future years for both zones. The 35-70 mm spat generally result in a higher correlation with the fishery data than the 5-34 mm spat, indicating that this size-class may be a more reliable measure of abundance.

Zone 2 (Eighty Mile Beach)

Figure 11 shows a comparison of piggyback spat data collected as part of FRDC project 92/147 (Joll, 1996) with the fishery catch rates at 1 and 2 year time lags in Zone 2. These figures show that the spat collection rates reflected both the increase and decrease in fishery catch rates during the early to mid 1990's. The best fit in Zone 2 appears to be with catch rates at a 2 year time lag. Fig 12 shows a comparison of spat collection rates with standardised fishery catch rates. Although the fit is not quite as good as for raw catch rates, the same trends are observed. Given that the spat collection rates are an index of juvenile abundance of 0+ age, the high correlations with fishery catch rates suggest that pearl shells caught per diver hour is an adequate index of recruitment, even though it may contain 2 - 3 year classes.

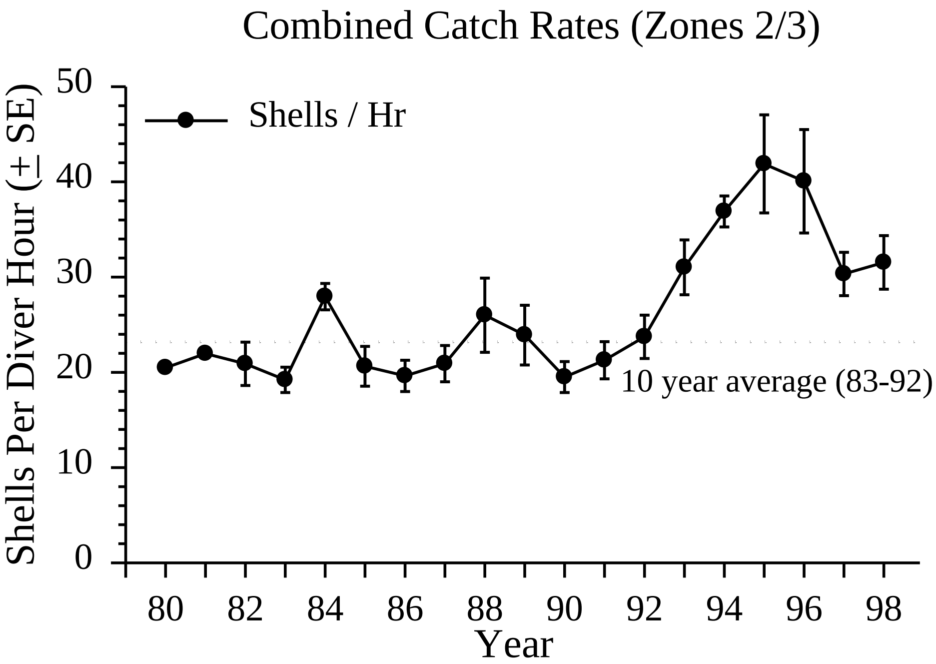

Figure 8. Raw catch rates (pearl shell caught per diver hour) in Zones 2 and 3 of the WA Pearl Oyster fishery during 1980 - 1998. For reference, the 10 year average prior to the increases in the early 1990's is plotted. Standard errors are based on data from individual 10 x 10 mile fishing grids.

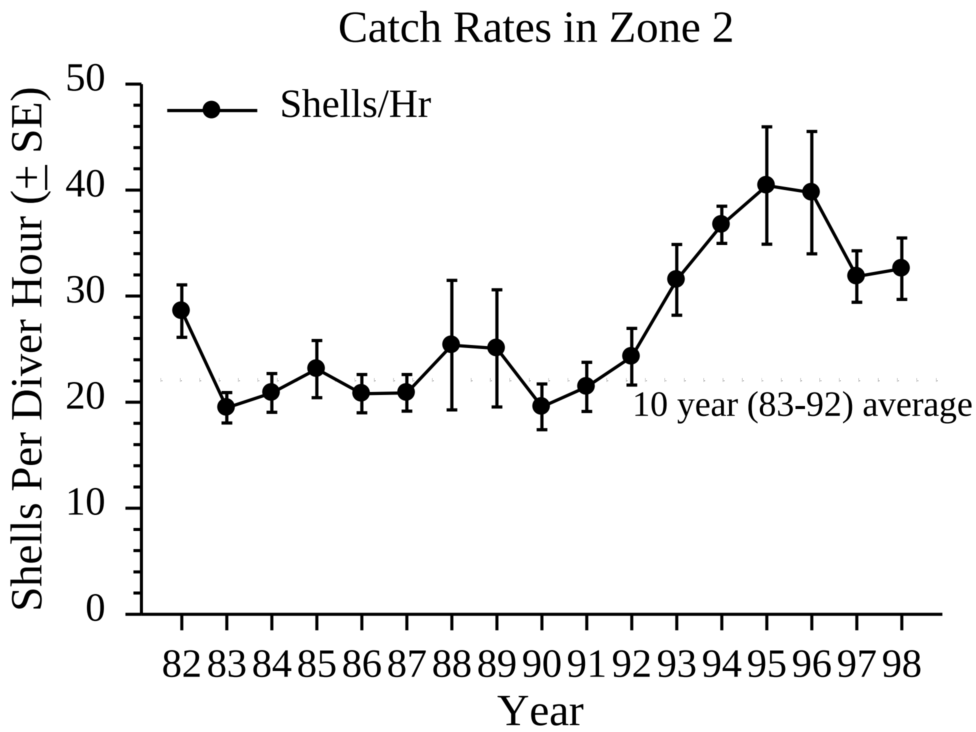

Figure 9. Raw catch rates (pearl shell caught per diver hour) in Zone 2 of the WA Pearl Oyster fishery during 1982 - 1998. For reference, the 10 year average prior to the increases in the early 1990's is plotted. Standard errors are based on data from individual 10 x 10 mile fishing grids.

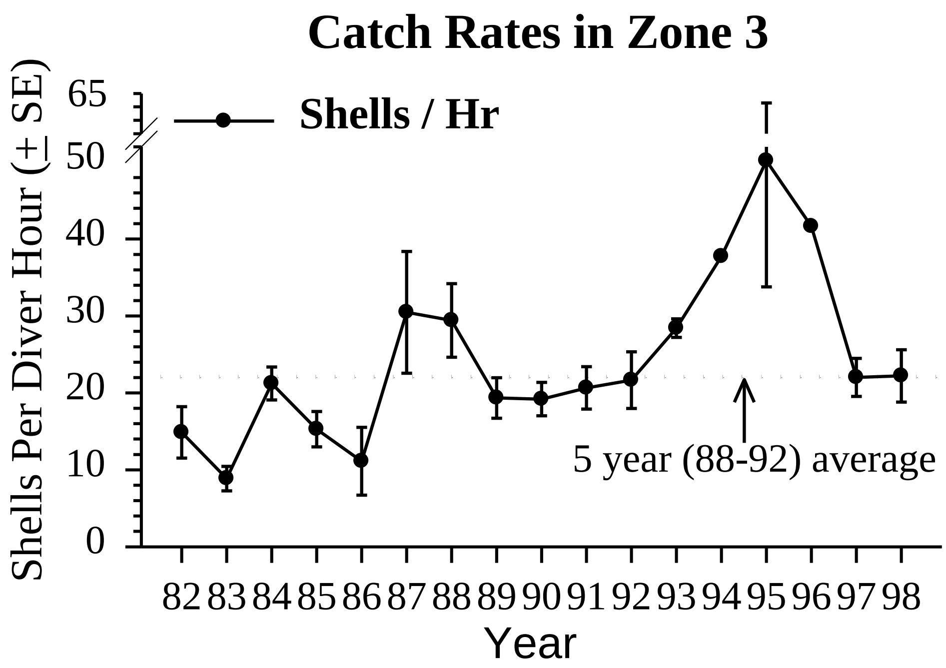

Figure 10. Raw catch rates (pearl shell caught per diver hour) in Zone 3 of the WA Pearl Oyster fishery during 1982 - 1998. For reference, the 5 year average prior to the increases in the early 1990's is plotted. Standard errors are based on data from individual 10 x 10 mile fishing grids. In 1994 and 1996, only 1 grid was fished.

Table 2
Correlations between collection rates of piggyback spat and catch per unit effort in the pearl oyster fishery. Data for spat collection rates is divided up into size classes. For Zone 2, standardised spat catch rates were also examined. Some of these correlations are expected to be spurious (see text). n = 5 for Zone 2; n = 4 for zone 3. Significant correlations ($p < 0.05$) highlighted in bold.

	Zone 2 - Raw spat collection rates			Zone 2 - Standardised spat collection rates			Zone 3 - Raw spat collection rates		
Fishery Catch Rates	Total	5-34mm	35-70mm	Total	5-34mm	35-70mm	Total	5-34mm	35-70mm
Raw: 1 year lag	0.84	**0.94***	0.43	0.83	0.87	0.61	0.58	**0.98***	-0.22
Raw: 2 year lag	0.87	0.68	**0.98***	0.44	0.17	0.65	0.35	-0.19	0.63
Standardised: 1 year lag	**0.91***	**0.92***	0.65	0.74	0.69	0.67	0.50	**0.99***	-0.34
Standardised: 2 year lag	0.75	0.63	0.76	0.16	-0.03	0.26	0.41	-0.05	0.57

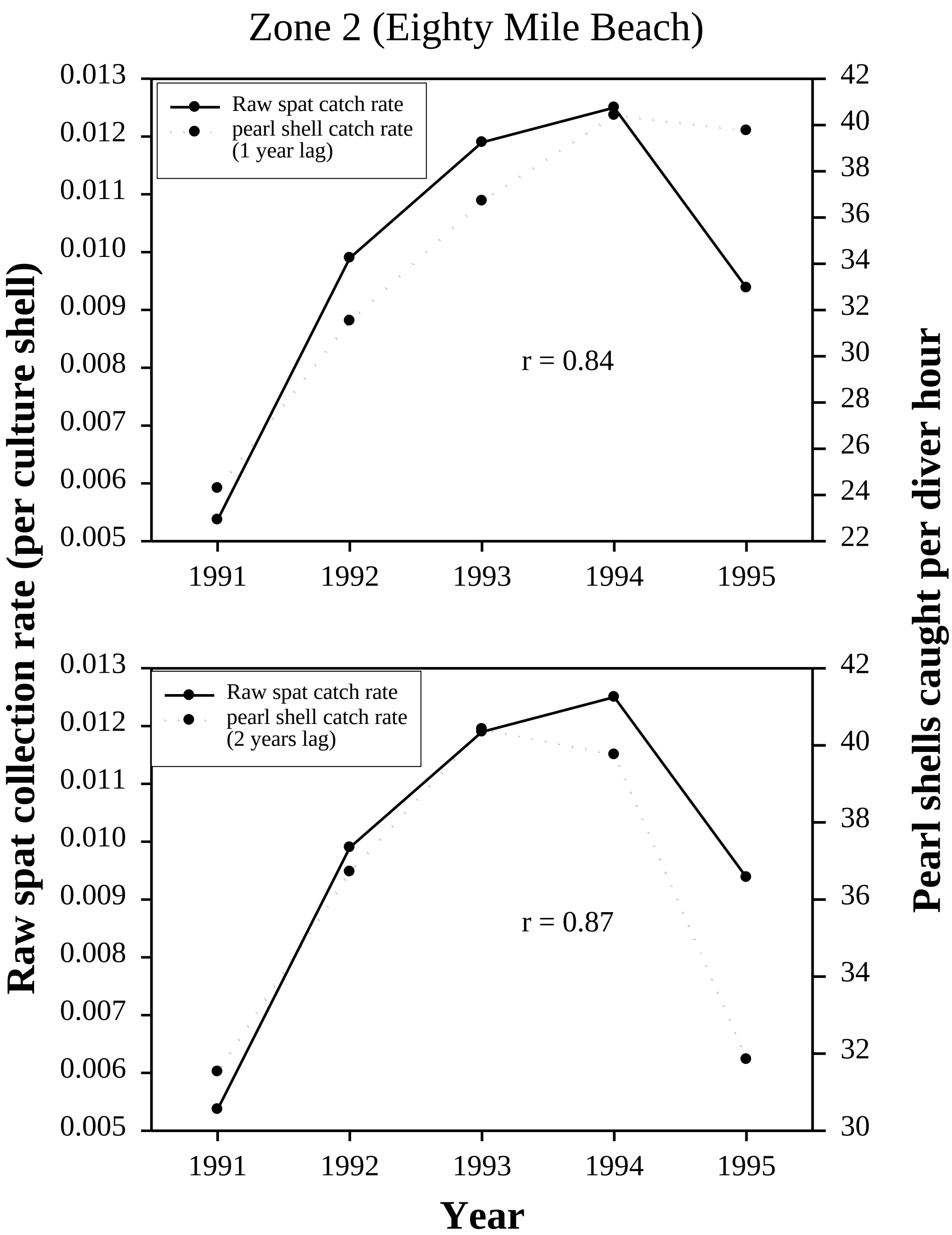

Figure 11. Piggy back spat collection rates (proportion of culture shell with spat) during 1991 - 1995, compared with raw pearl shell catch rates at 1 and 2 year lags.

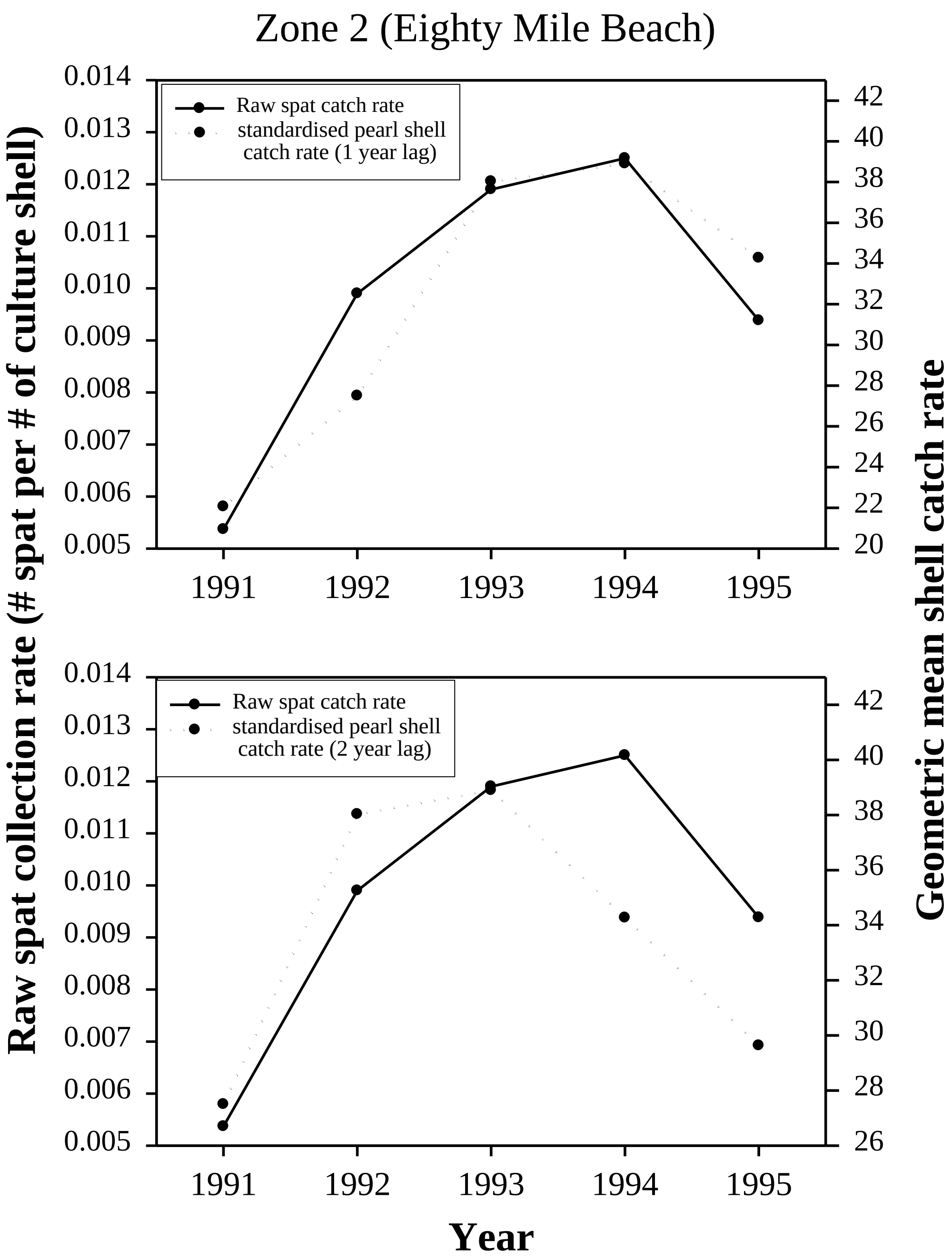

Figure 12. Piggy back spat collection rates (proportion of culture shell with spat) during 1991 - 1995, compared with standardised pearl shell catch rates at 1 and 2 year lags.

Figure 13 shows the data for the most significant correlations of spat collection rates and fishery catch rates in Zone 2. Small spat (0-34mm / 0+ age group) correlated well with the fishery catch rates at a 1 year time lag, however this has no real biological interpretation as it would take spat this size 1.5 - 2 years to enter the fishery. This spurious correlation is due to both indices increasing over this short period of time (Fig. 13A). Large spat (35-70mm) predicted well the fishery catch rates at a 2 year lag (Fig 13B) which fits in with the growth period required. When accurate size-frequency data for the pearl oyster fishery is available, it will be easier to correlate single year classes from both spat data and fishery data.

Zone 3 (Lacepede Channel)

Figure 14 and Table 2 show a comparison of piggyback spat collection rates with the fishery catch rates at 1 and 2 year time lags. The fits are not as good as for zone 2 when looking at the entire set of spat data. However, the correlations for the 35-70 mm spat and 2 year lag are about 0.6 (Table 2) and describe the general increase and decrease in fishery catch rates reasonably well, but there are only 4 data points. While the Lacepede Channel spat length frequency generally shows one modal class the mode varies between years and it may be worthwhile examining the abundance of the different size classes separately and combined to assess the impact on the recruitment to the fishery at the different lags (Table 2).

In summary, a close correlation was found between spat collection rates and fishery catch rates during the 5 year period (4 years in zone 3) when the piggyback spat data was available. In zone 2, spat collection rates were a good predictor of fishery catch rates at a 2 year lag. In zone 3, large spat (35-70mm) were positively correlated with catch rates at a 2 year lag (Table 2), however this was not significant due to the low sample size (n = 4). Because of the few number of data points available these results are still very preliminary. However, the conclusion is that spat catch rates are sufficiently adequate representation of recruitment to enable them to be used as a proxy recruitment index when examining the longer term question of environmental influences on recruitment of pearl oysters into the fishery.

5.2.3. The effect of environmental factors on recruitment into the pearl oyster fishery

Sea Surface Temperature

Results of correlation analyses between catch per unit effort (raw and standardised) and sea surface temperature (SST) are shown in Table 3. No significant correlations were detected for any of the comparisons, in either Zone 2 or Zone 3 of the fishery. Therefore there is no indication that sea surface temperatures at the time of spawning and settlement (Nov-Dec), have had a major influence on recruitment into the fishery. However, it needs to be recognised that temperature is an important feature in annual breeding cycles of most marine animals, and the absence of a significant correlation does not imply that temperature is not important. It is likely that other factors are also involved in the process, and that these interact in a complex manner.

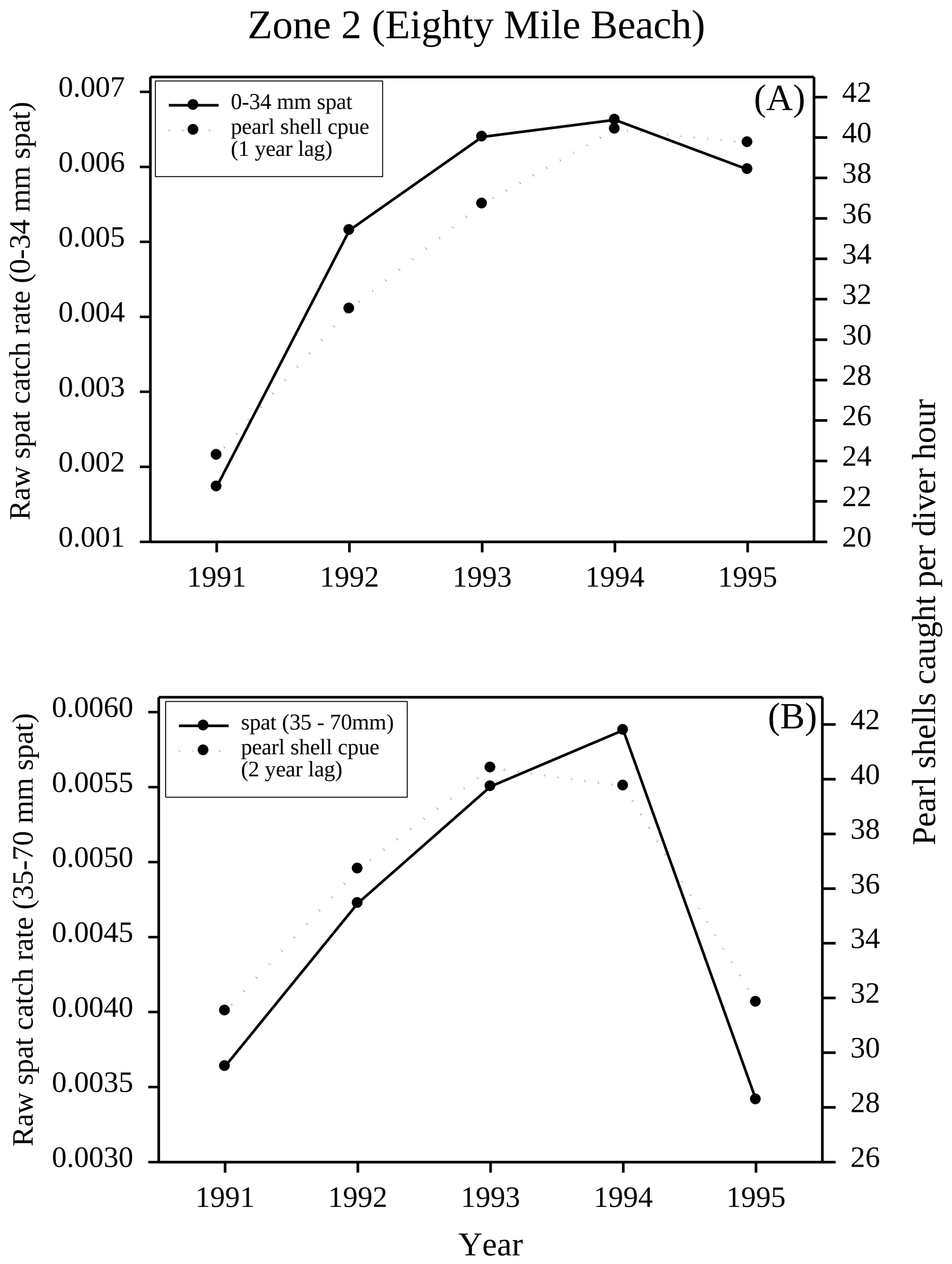

Figure 13. A) Spat collection rates for 0-34mm spat vs raw pearl shell catch rates at a 1 year time lag. This relationship is expected to be spurious (see text); B) . Spat collection rates for 35-70mm spat vs raw pearl shell catch rates at a 2 year time lag. Years indicate time when spat data was collected.

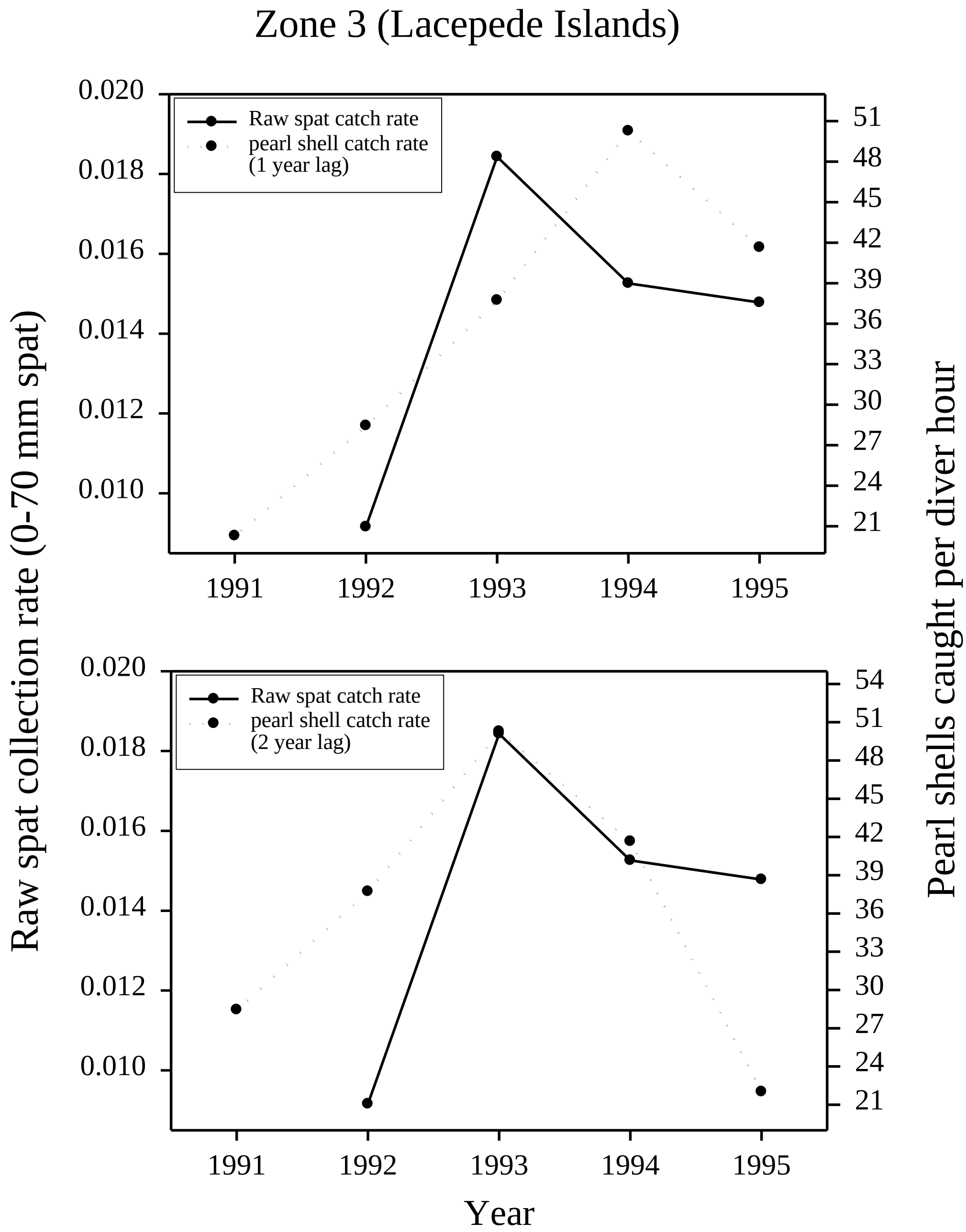

Figure 14. Piggy back spat collection rates in Zone 3 during 1992 - 1995, compared with raw pearl shell catch rates at 1 and 2 year lags.

Table 3
Correlations between Sea Surface Temperature (SST) during the months of spawning and settlement (November and December), and catch per unit effort in the pearl oyster fishery. 1 - 4 indicates time lags of 1 - 4 years.

	Zone 2 (Broome)			Zone 3 (Lacepde Channel)			Zone 2/3 (combined catch rates)		
	Nov	Dec	Nov/Dec	Nov	Dec	Nov/Dec	Nov	Dec	Nov/Dec
Raw catch rates									
SST 1	0.24	0.34	0.31	0.41	0.38	0.42	0.19	0.33	0.28
SST 2	-0.09	0.15	0.04	0.13	-0.07	0.12	-0.11	0.15	0.04
SST 3	-0.22	0.03	-0.11	-0.15	-0.35	-0.26	-0.24	0.03	-0.17
SST 4	-0.18	-0.22	-0.23	-0.37	-0.39	-0.43	-0.16	-0.22	-0.22
Standarised catch rates									
SST 1	0.20	0.43	0.34	-0.02	0.14	0.06	0.16	0.40	0.31
SST 2	-0.02	0.13	0.07	-0.11	0.23	0.05	-0.03	0.16	0.08
SST 3	-0.11	0.00	-0.06	0.03	-0.06	-0.01	-0.12	-0.05	-0.10
SST 4	-0.04	-0.07	-0.06	0.03	-0.14	-0.07	-0.06	-0.10	-0.09

Rainfall

Results of correlation analyses between catch per unit effort (raw and standardised) and rainfall (as an index of freshwater input) are shown in Table 4. Minimal data exist for rainfall in Zone 3 areas, so these were not considered separately. Significant correlations were detected for rainfall at one and two year lags, particularly for the month of December (Table 4) in Zone 2, for both raw and standardised catch rates. Thus there is some evidence that rainfall during the spat/juvenile phase of *P. maxima* may have an influence on recruitment into the fishery. This suggests that assessment of the impact of cyclones during December-April on the settled spat should be examined further.6 However, it needs to be recognised that these tests are conducted under Type I error rate of 0.05. Therefore, in the case of rainfall where 48 individual correlations with catch rates were made, it would be expected that at least 2 of these would be significant just by chance alone.

Southern Oscillation Index (SOI)

Correlations between annual SOI and catch rates at 1 - 4 year lags are shown in Table 5. Significant correlations were observed between catch rates and annual SOI at a 2 year time lag in Zone 2 and Zone 3 of the pearl oyster fishery. In Zone 2, the significant correlation was with raw catch rates, while in Zone 3 it was with standardised catch rates. Thus we propose the hypothesis that El Nino conditions 2 years prior to recruitment to the fishery (which would affect both spat and juvenile survival) are a positive influencing factor on recruitment to the pearl oyster fishery. This is reflected in the peaks in recruitment in 1984, 1988 and 1993-96 (Fig. 8) occurring about 2 years after the ENSO events 1n 1982-83, 1986-87 and 1991-94.

Sea Level Height (Fremantle)

Results of correlation analyses between catch per unit effort (raw and standardised) and Sea Level Height are shown in Table 6. No significant correlations were detected for any of the comparisons, in either Zone 2 or Zone 3 of the fishery. Therefore there is no indication that strength of the Leeuwin Current, as shown by SLH, has had a major influence on recruitment into the fishery. However, SLH as shown pertains to that measured in Fremantle, which is a considerable distance from the main 80 Mile Beach pearl oyster grounds. Also, November-December is a period when the Leeuwin Current is at its weakest. Therefore this measure may not be as applicable as the SOI. In support however, previous studies have shown that SLH (measured at Fremantle), is a valid indicator of the strength of the Leeuwin Current. It has been demonstrated to have a significant effect on prawn and scallop fisheries in Shark Bay, approximately 1000km north of Fremantle (Caputi et al. 1998). Further investigations should focus on the lag between sea level at Fremantle vs sea level at Broome (which may be about 2 months) and assess the impact of the current variation during all months of the year.

Table 4
Correlations between Rainfall and catch per unit effort in the pearl oyster fishery. 1 - 4 indicates time lags of 1 - 4 years. Significant results highlighted in bold

	Zone 2 (Broome)		Zone 2/3 (combined catch rates)	
	Nov	Dec	Nov	Dec
Raw catch rates				
Rainfall 1	-0.30	**0.72***	-0.23	**0.70***
Rainfall 2	-0.20	**0.58***	-0.18	**0.60***
Rainfall 3	-0.26	0.30	-0.21	0.30
Rainfall 4	-0.27	-0.07	-0.21	-0.09
Geometric mean catch rates				
Rainfall 1	-0.23	**0.71***	-0.22	**0.69***
Rainfall 2	-0.26	0.44	-0.24	0.45
Rainfall 3	-0.20	0.09	-0.21	0.08
Rainfall 4	-0.26	0.09	-0.26	-0.17

Table 5
Correlations between Southern Oscillation Index (SOI) and raw and standardised (geometric mean) catch rates in the pearl oyster fishery. 1 - 4 indicates time lags of 1 - 4 years. Significant results highlighted in bold.

	Zone 2 Raw catch rates	Zone 2 Standardised catch rates	Zone 3 Raw catch rates	Zone 3 Standardised catch rates
SOI 1	-0.18	-0.18	-0.28	-0.40
SOI 2	**-0.56***	-0.36	-0.47	**-0.58***
SOI 3	-0.37	-0.37	-0.36	-0.06
SOI 4	-0.13	-0.21	-0.09	-0.14

Table 6
Correlations between Sea Level Height at Fremantle (SLH) and raw and standardised (geometric mean) catch rates in Zone 2 of the pearl oyster fishery. 1 - 4 indicates time lags of 1 - 4 years

	November	December	Nov/Dec
Raw catch rates			
SLH 1	0.28	0.28	0.30
SLH 2	-0.26	-0.23	-0.26
SLH 3	-0.26	-0.44	-0.40
SLH 4	-0.14	-0.18	-0.19
Standardised catch rates			
SLH 1	0.19	0.17	0.19
SLH 2	-0.09	-0.13	-0.12
SLH 3	-0.27	-0.33	-0.34
SLH 4	-0.20	-0.13	-0.19

Multiple Regression Analyses

The correlation analysis identified that a 2 year lag for catch rates was significantly correlated with certain variables in both Zone 2 and Zone 3. The biological interpretations of this indicates that the environment has a major impact during the spat phase. This relationship was further investigated via multiple regression analysis (Table 7.)

Sixty nine percent of the variability ($R^2 = 0.69$) in raw pearl shell catch rates in Zone 2 was explained by 3 environmental variables at a 2 year time lag (Table 7). Of these variables, rainfall in December and the Southern Oscillation Index had a significant influence on the variation in catch rates. Rainfall was deemed the most significant, and was correlated positively with catch rates. SOI was negatively correlated with catch rates, suggesting that settlement and/or juvenile survival was enhanced during El Nino years. It is worth noting that rainfall in November had no influence on catch rates, although generally this month receives little or no rainfall. Future research on rainfall should focus more closely on the months December to April to assess the impact of the summer monsoon and/or cyclones on the spat and juvenile phase of *P. maxima.*

Similar results were seen in Zone 3. In this zone, 66% ($R^2 = 0.66$) of the variability in catch rates was explained by sea surface temperature and the southern oscillation index 2 years previously (Table 7). SST had a significantly positive influence on catch rates, and SOI was negatively correlated with catch rates. This is more evidence suggesting that larval and/or juvenile survival was enhanced during El Nino years.

In summary, the multiple regression analyses confirmed what was initially suggested by correlations, namely that environmental conditions two years prior to pearl oysters recruiting into the fishery had a significant influence on the catch rates. Catch rates were higher two years after El Nino conditions, as indicated by the negative relationships with SOI. The fact that this occurred in both Zone 2 and Zone 3 further strengthens the hypothesis of El Nino conditions having a significant influence on recruitment of *P. maxima* into the pearl oyster fishery, via the mechanism of improved larval success and/or juvenile survival.

It needs to be noted however, that some of the evidence for this relationship arises from one major ‘spike’ in catch rates, which occurred at the same time as GPS technology was being adopted by the industry. The influence of GPS technology on fishing efficiency cannot be underestimated, as demonstrated in the northern prawn fishery (Robins et al. in press). This study found that after a 3 year period vessels with GPS plotters increased their fishing efficiency by 12%. Early evidence indicates that catch rates in the WA pearl oyster fishery have stabilised at around 30 shells per hour, which is approximately 30% higher than historical averages prior to the increase. However, despite skippers becoming more familiar with the use of GPS and more sophisticated in its use, catch rates have returned from their ‘spike’ values to levels closer to the long-term mean, which would indicate that the spike at the time of

GPS introduction is not a catching power artefact. Further long-term study of the fishery and environmental variables will clarify the relationship between environment, GPS technology, and fishing fleet behaviour, and how these affect stock abundance as measured by fishery catch rates.

Table 7
Multiple regression results for the influence of environmental variables on recruitment (measured by fishery catch rates 2 years after settlement) of *Pinctada maxima* into the pearl oyster fishery. Variables are arranged in descending order of importance. B = partial regression coeffcient, Beta = standardised partial regression coefficient, Tolerance is a measure of the collinearity (see methods). Significance of models and proportion of variance explained are: Zone 2: $F(3,10) = 7.35$; $P<0.01$; $R^2 = 0.69$; Zone 3: $F(2,11) = 10.5$; $P<0.01$; $R^2 = 0.66$

Variable	B	Beta	Partial correlation	Tolerance	t-value	P-value
			Zone 2 (annual catch rates)			
Intercept	120.2					
Rainfall (December)	0.07	0.62	0.73	0.92	3.22	0.01
Southern Oscillation Index	-0.58	-0.52	-0.64	0.80	-2.51	0.03
Sea Surface Temperature (Dec)	-3.41	-0.35	0.19	-0.51	-1.89	0.09
			Zone 3 (Standardised catch rates)			
Intercept	-228					
Sea Surface Temperature (Dec)	8.51	0.60	0.70	0.95	3.29	0.01
Southern Oscillation Index	-0.63	-0.43	-0.58	0.95	-2.35	0.04

7. Benefits

This study has highlighted for the first time the potentially crucial importance of environmental influences on recruitment to the WA pearl oyster fishery. From this a number of recommendations have arisen (see section 9) which will enhance the management of the wild fishery and provide for greater certainty and predictability of the quota levels. Furthermore, the biological knowledge of growth rates has been expanded to now include all the main sectors of the fishery. Correspondingly, the long term sustainable management of the pearl oyster fishery will become more robust.

8. Further development

The relationships between diver catch rates and environmental variables identified during this study will be further examined as part of the on-going stock assessment and management of the pearl oyster fishery. The study has also shown that industry derived data calibrated through independent studies can provide a particularly cost effective means of monitoring the status of pearl oyster stocks. As more years of data are collected and analysed, and the quality of the data improves (see Recommendations below) a better understanding of this relationship will be achieved.

9. Conclusions

9.1. Summary and conclusions

The results demonstrated clearly that pearl oysters recruit into the fishery in their third year of life. At the Lacepede Channel (Zone 3) pearl oysters grow through the exploitable size classes over 2 years, similar to the 80 Mile Beach stock (Zone 2) . In contrast, at Exmouth Gulf (Zone 1) pearl oysters remain in the fishery for at least 3 years. In Zones 2 and 3 catch rates for the fishery (shells caught per diver hour) were positively correlated with piggyback spat collection rates. It needs to be noted however, that some of the evidence for this relationship arises from one major ‘spike’ in catch rates, which occurred at the same time as GPS technology was being adopted by the industry. Therefore, at this stage we propose the hypothesis that environmental conditions during the spat and juvenile phase, particularly those related to El Nino conditions, have a significant influence on survival and consequently, stock abundance. This effect, if it exists, should be reflected in catch rates of the fishery, 2-4 years after settlement, depending on the age classes of the catch. This hypothesis can, and will be tested, by collecting and analysing fishery (catch rate and size composition data) and piggyback spat settlement data over the long-term, in conjunction with environmental information.

9.2 Recommendations

A number of recommendations on future research have arisen from this study. These are:

- The piggyback spat settlement program be restarted to obtain a reliable measure of year-class strength.
- The usefulness of fishery catch rates would be enhanced if size frequency data were available for the commercial catch. A research program involving the collection of this data is being proposed.
- The influence of environmental variables on recruitment needs to be incorporated into annual stock assessment in the WA Pearl Oyster Fishery.
- A standardised catch rate index which incorporates both fleet dynamics and historical changes in technology should be developed for the WA Pearl Oyster

Fishery. This would provide better data against which to examine environmental influences, particularly if the catch rate data could be examined by size.

- The relationship between “piggyback” spat settlement, environmental effects and recruitment to the fishery which.can be used to forecast increases/decreases in abundance should be developed. This enables changes to quota to be forecast to allow forward planning in pearl seeding and farm operations.

10 References

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11. Appendix 1: Intellectual Property

No Saleable items were developed during this study.

12. Appendix 2: Staff

Staff that were employed on the project using FRDC funds were Mr Craig Skepper and Mr Clinton Syers.

Staff who assisted on the project using non-FRDC funds were Dr Anthony Hart, Mr Boze Hancock, Mr Chris Dibden, Mr Rod Pearn, Mr Frank Fabris and Mr James Murray. The crew of the RV 'Flinders' assisted with the set-up of the Lacepede Island tag site. Dr Yuk Wing Cheng carried out the statistical analysis for growth.

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