Predicting and assessing recruitment variation – a critical factor for management of the *Pinctada maxima* fishery in Western Australia

Anthony Hart and David Murphy

Department of Fisheries

Australian Government

Fisheries Research and Development Corporation

Fish for the future

FRDC Project No. 2000/127

Predicting and assessing recruitment variation – a critical factor for management of the Pinctada maxima fishery in Western Australia

Anthony M. Hart, David Murphy

Published by the Department of Fisheries Research Division, PO Box 20 NORTH BEACH, Western Australia 6920

JUNE 2006

The Fisheries Research and Development Corporation plans, invests in, and manages fisheries research and development throughout Australia. It is a federal statutory authority jointly funded by the Australian Government and the fishing industry.

Table of Contents

Non Technical Summary

1998/153 Predicting and assessing recruitment variation – a critical factor for management of the Pinctada maxima fishery in Western Australia

PRINCIPAL INVESTIGATOR: Dr Anthony M. Hart

ADDRESS: Department of Fisheries
Western Australian Fisheries and Marine Research Laboratories, P.O. Box 20, North Beach 6920
Western Australia
Telephone: 08 9203 0111 Fax: 08 9203 0199
e-mail: ahart@fish.wa.gov.au

OBJECTIVES:

1. To establish set protocols for piggyback spat sampling within the pearl oyster fishery and develop a database for the storage of data collected.
2. To establish set protocols for length frequency sampling within the pearl oyster fishery and develop a database for the storage of data collected.
3. To establish a database of factors affecting catch rate.
4. To examine links between spat sampling data set, environmental factors and the abundance estimates for the pearl oyster fishery.

OUTCOMES ACHIEVED

A recruitment and length-frequency monitoring program was developed for the pearl oyster (*Pinctada maxima*) fishery in Western Australia. The program uses both research and industry personnel to collect settlement data ('piggyback spat') from adult shells, and age class information from length-frequency measures. Five years of spatio-temporal settlement data for two species (*P. maxima* and *P. albina*) were analysed and used to generate a predictive stock index for management purposes, using information from the age 0+ and 1+ indices for *P. maxima* settlement, spatially delineated by the major fishing grounds. An exceptional 0+ settlement measured in 2005 provided a 4 to 6 year forward prediction of record stock levels in 2009-2011, although the result is considered preliminary until confirmed by the 1+ age index of 2006. Industry and managers have accepted the information, and the decision rule framework for fishery management is being revised to include the predictive information.

Historically, total allowable catches (TAC) in the pearl oyster fishery have been changed in response to significant fluctuations in the previous year's catch rate (catch per unit effort), in lieu of other information on oyster abundance. However, in a gauntlet fishery that targets only 3 year classes, this approach is sub-optimal, and a need to more closely align TAC with stock abundance was identified. To achieve this, information was needed on: 1) the size structure (length frequency) of past catches; 2) abundance of pre-recruits (piggyback spat); 3) environmental variables affecting stocks; and 4) other factors affecting catch rate such as water clarity, and the use of new technology (e.g. GPS).

Newly recruited spat (i.e piggyback spat) on commercially harvested *Pinctada maxima* were separated into two age classes (0+, 1+), using length-frequencies. This was made possible by the fact that the primary spawning months are October to December. Industry and research personnel on board vessels carried out sampling during the fishing season over the 5 years of the project. A total of 600,000 shells were sampled for measurement of piggyback spat and 120,000 for length frequency. The sampling protocol utilised the drift-dive profiles employed by the industry (8+ drift dives per day). Size-frequency data were collected on drifts 2 and 5, and spat data on all other drifts. All data were entered into a database, imported into a GIS program, and mapped by their respective GPS positions into the relevant spatial entities (fishing area or ‘patches’).

To further elucidate the nature of settlement in this species, larval dispersion patterns of *Pinctada maxima* were modelled by tracking particles transported by ocean currents estimated from a circulation model for the North West Shelf. Particle trajectories were used to estimate both potential settlement sites and potential spawning sites. Spawning distributions were based on a broodstock (Mother-of-Pearl or MOP) survey conducted in September 2001, while settlement distributions were based on the first three years (2001-2003) of spat survey data collected during this project. Analyses were restricted to Zone 2 (the 80 Mile Beach area), where most of the stocks are found.

Abundance of 0+ age class *Pinctada maxima* differed significantly between years, however there was a significant interaction between year and area, indicating that temporal trends were area specific. Depth and month of sampling were also found to influence settlement rates, with the inshore, shallower areas receiving the higher settlement, which is also likely to be a habitat effect. Evidence for fishing ground connectivity was found, with a significant positive correlation in settlement of 0+ *Pinctada maxima* between the three areas at the centre of the fishery (5-8 Mile; 10 Mile; 14-21 Mile). For those areas further apart, correlations between settlement were not significant. In Zone 2 of the fishery (80 Mile Beach) there was a positive correlation between 0+ spat abundance and 1+ spat abundance one year later for the industry data ($n = 5$; $r = 0.68$), and the research data ($n = 4$; $r = 0.74$). In Zone 3 (Lacepede Islands), there was a significantly positive correlation ($r = 0.93$) between 0+ spat (Year n), and 1+ spat (Year $n + 1$). These positive correlations between settlement year classes enabled predictions of future CPUE and the development of a preliminary management rule utilising this information.

Modelling of larval transport and broodstock spawning areas showed distinct patterns in settlement that corresponded to observed distributions. For settlement distribution, results averaged across the model runs indicated two main potential settlement areas. The larger was centred just inshore of the 10 m depth contour (121°24’E, 19°6’S – 10 Mile Pearl Patch), with the smaller centred just inshore of the 20 m depth contour (121°7’E, 19°11’S). The relative settlement rate in the two areas varied from year to year. Overall, the model predicted settlement region covered nearly all the areas surveyed for spat, with predicted high settling rates corresponding with the main survey area.

Estimated spawning areas associated with the surveyed spat distributions were centred just inshore of the 10 m depth contour (121°24'E, 19°6'S – 10 Mile Pearl Patch), but relatively high values extended offshore almost to the 20 m depth contour and onshore almost to the coast. Apart from extending into very shallow water, the spawning area estimated from the surveyed spat was consistent with the surveyed MOP distribution.

Length-frequencies of the commercial catch of *P. maxima* in Zone 2 were stable in distribution over time, compared to Zone 3 where the mode oscillated up and down, presumably reflecting variable year class strengths. This was hypothesised to be an effect of irregular recruitment in Zone 3, compared to Zone 2. There was a significantly higher variability in 1+ settlement in Zone 3 (s^2 = 17.5), compared to Zone 2 (s^2 = 1.2) ($F = 0.07$; $p < 0.01$). In general, research and industry personnel obtained similar measurements of the size-frequency of *P. maxima*, but it was not entirely consistent over time or spatial area. For the 10 Mile Pearl Patch, there was general agreement between methods over all years, with the exception of the 125-130 mm size class. In the 14-21 Mile Pearl Patch, a disparity in size-class representation was more evident between the two sampling methods. Reasons for this are not clear; it may be due to the measuring protocols, or shell selectivity rules used by different pearl companies, which are in turn affected by the visibility. Poorer visibility generally results in a broadening of the size classes fished as the rigour of the size selectivity is reduced

In summary, the project achieved its goal of developing a formal sampling regime to estimate recruitment and age-class abundance within the commercially fished oyster stocks, with a view to obtaining a predictive stock index. There was agreement amongst industry and research datasets as to the nature of the temporal trends in settlement, particularly in the 0+ age class, although some disparities existed between datasets for the length-frequency data. The centre of settlement distribution and spawning areas within the main fishery (10 Mile Pearl Patch) was verified by oceanographic modelling of larval transport and connectivity between populations was established by positive correlation indices. There was significant potential for industry data to provide the recruitment index and length-frequency data, provided the protocols of sampling are adhered to. Overall, the project has resulted in a significant advance in our biological knowledge, and consequently, management capacity to ensure the future sustainability of the *Pinctada maxima* stocks in Western Australia.

KEYWORDS: silver-lipped pearl oyster, *Pinctada maxima,* settlement, recruitment, piggyback spat, length-frequency sampling, larval transport, oceanographic modelling

Acknowledgements

This project owes it success to the support of the Western Australian Pearling Industry, specifically Paspaley Pearling, Broome Pearls, Maxima Pearling, Morgan's and Co.

Dr Scott Condie of CSIRO Marine (Hobart) was contracted to undertake the oceanographic modelling and larval transport aspects of this project.

Fisheries Technical officers assisting in the project were Frank Fabris, Katie Weir, Jamie Colquhoun, Max Coyne, and Jamin Brown. Many thanks to them. Jamin Brown also assisted with the preparation of many of the figures in this report.

Jim Penn and Nick Caputi, provided valuable guidance on final analyses and recommendations.

Finally, we thank the Fisheries Research and Development Corporation for the financial resources provided, without which this project would not have been possible.

1 Background

Pearl oysters used for the production of South Sea Pearls in Australia are derived mostly from wild stocks. The setting of fishing limits (quota) for silverlip pearl oysters is decided through the examination of previous year's catch rates (shells caught per hour dived). The exclusive use of retrospective catch data has meant that biologists and fisheries managers have often been put in a difficult position when deciding quota changes, as past catch rates do not always give a clear indications of future stock abundance.

Department of Fisheries Western Australia has conducted various studies on wild stocks of pearl oysters to provide the knowledge-base necessary to evaluate the status of wild stocks. In assessing recruitment variation (FRDC 95/41), a strong relationship was identified between the abundance of silverlip juveniles on adult shells (piggyback spat) and subsequent catch rates of adult pearl oysters. It was found that catch rates of culture shell were positively correlated with levels of piggyback spat (1+ size) recorded two years previously.

As the pearl oyster fishery is run as a "gauntlet" fishery, with individuals vulnerable to capture at between 3 and 6 years of age, knowledge of shell sizes in the catch can allow monitoring of the progression of yearly cohorts into, and through the fishery. This can allow predictions of new recruitment to areas to be confirmed and recruitment declines to be identified, however the size of fished pearl oysters fished reflects the preferred size, and may not reflect the movement of cohorts through the fishery unless the fishing is poor. At present there is limited collection of catch length frequency data.

In FRDC project 95/41, a strong correlation was also identified between the catch rate of culture shell and major environmental factors e.g. rainfall and ENSO events. These preliminary relationships were identified despite the fact that catch rates comprise two or more year classes of culture shell (Hart et al., 1999). However, it was also recognised that the effects of GPS technology on commercial catch rates had yet to be thoroughly analysed, hence there was a need to revisit these environmental relationships with catch rates, while taking into account fishing efficiency increases as a result of GPS technology.

2 Need

Historically, total allowable catches (TAC) of respective zones in the pearl oyster fishery have been changed in response to significant fluctuations in the previous year's catch rate (catch per unit effort). These changes, however, have been influenced by factors other than variations in stock abundance, e.g. changes in available technology or variations in fishing efficiency due to weather conditions or water clarity.

In order to make more reliable projections on future catch and effort there is a need to move away from reliance on retrospective catch data for management. In order to do this, information supplied to decision makers should include: 1) the size structure (length frequency) of catches; 2) information on the abundance of pre-recruits (piggyback spat); 3) information on important environmental variables affecting recruitment; 4) other factors affecting catch rate such as water clarity, and the use of new technology (e.g. GPS), and 5) the relationship of pre-recruits to commercial catch rates. Such information will complement the data on length frequencies of the entire stocks obtained by research surveys every 5 – 7 years.

A recommendation from Project No. 95/41 states:
"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."

A framework for the collection of this data is needed, as pearl oyster fisheries have large fluctuations in recruitment over time, and management needs to base quota decisions on the presence or absence of emerging year classes. Collection of this data will give a more stable signal on the "health" of the fishery and allow more confident predictive assessments to be made.

2.1 Objectives

1. To establish set protocols for piggyback spat sampling within the pearl oyster fishery and develop a database for the storage of data collected.
2. To establish set protocols for length frequency sampling within the pearl oyster fishery and develop a database for the storage of data collected.
3. To establish a database of factors affecting catch rate.
4. To examine links between spat sampling data set, environmental factors and the abundance estimates for the pearl oyster fishery.

3 Methods

3.1 Piggyback spat sampling.

Sampling of recruitment of *Pinctada maxima* was carried out in Zones 2 and 3 of the fishery, which produce more than 90% of the catch (Figure 1). It involved examining the catch of adult shell for the presence/absence of newly recruited spat (i.e. piggyback spat; Figure 2), which can be separated into two age classes, since the primary spawning months are October to December each year (Rose et al., 1990). In general, the 0+ age class is 4-7 months of age at time of sampling (March-June each year), and the 1+ age class is 16-21 months. It is likely that a small proportion of the 0+ and 1+ spat sampled will be outside these ages, as the breeding season can extend to March-April (Rose et al., 1990) however the size-frequency histograms generally show clear year classes.

There were four main logistical difficulties to overcome in order to obtain a valid index of abundance from the piggyback spat. First, was the low incidence rate of spat on adult shell, second was the necessity to gather data without interrupting the fishery catching and handling process, third was the requirement to train industry personnel to undertake the spat sampling, particularly as both ‘piggyback spat’ and ‘size-frequency’ sampling of the catch were required, and fourth was the co-occurrence of another ‘piggyback spat’ species on commercially caught *P. maxima*, that of *Pinctada albina*, which is difficult for an untrained eye to separate from *P. maxima,* especially when they are in the 0+ age class (Figure 4).

A series of photographic identification guides were compiled to assist identification. These displayed the essential differences between *Pinctada maxima* spat, and *Pinctada albina* spat (Figure 4). Industry personnel were required to hold all spat collected in freezers and send to the Research Division for correct identification of species.

Enlisting voluntary personnel from the pearl oyster fishing fleet, and dedicating two research personnel on board vessels during the fishing season resulted in large samples of the catch. The season is concentrated into about 10-12 fishing neaps (the slack-water time of the tide) over 3 months. Using the carefully controlled drift-dive profiles employed by the pearl divers, a sampling protocol was designed that yielded effective sample sizes for both spat and size-frequency (Table 1). A pearl drift is a 40

– 60 minute dive undertaken by between 2 and 8 pearl divers. Size-frequency data were collected on drifts 2 and 5, and spat data on all other drifts (Table 1). This protocol allowed the simultaneous sampling of spat and size-frequency from each vessel, and the assignment of drifts 2 and 5 to sampling the size-frequency of the catch ensured sufficient samples for both objectives. Distribution of sampling each year was proportional to the percentage of drift dives undertaken by the pearl diving fleet (Figure 3).

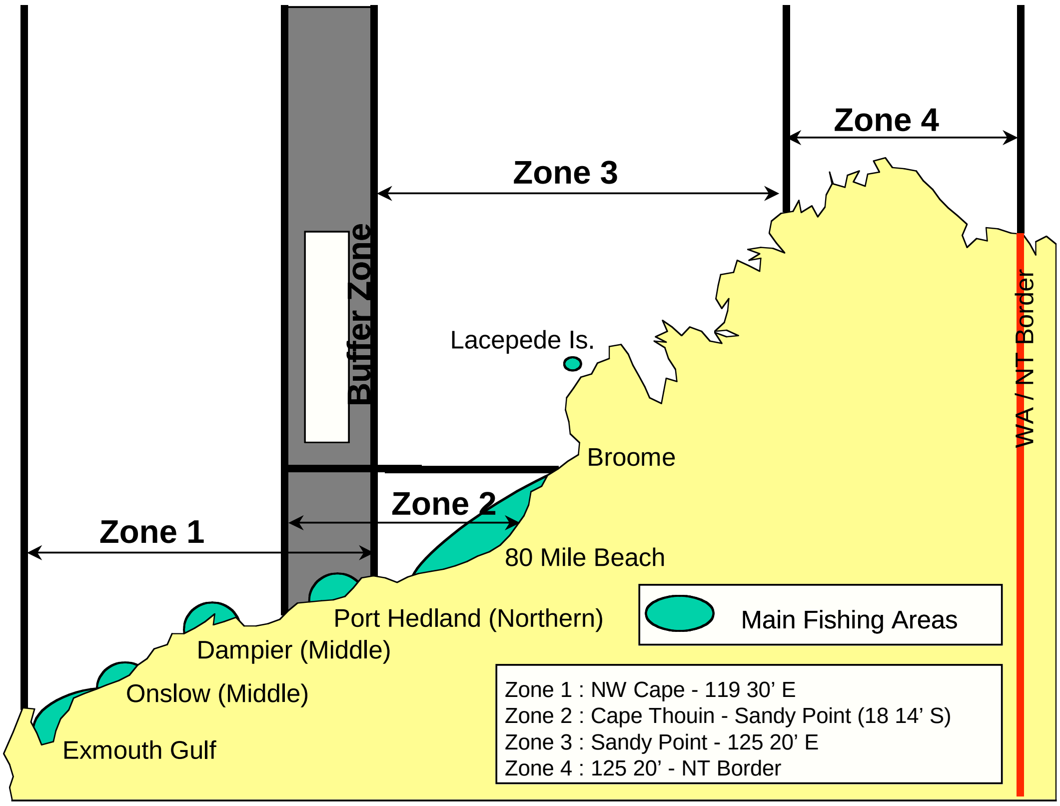


Figure 1. Management areas of the Western Australian Pinctada maxima fishery. The buffer zone is the area in which license holders in both Zone 1 and Zone 2 may harvest pearl shell.

Figure 2. An adult shell of *Pinctada maxima* with a 'piggyback spat' attached (see red circle). The spat is *Pinctada albina*, rather than *P. maxima*.

The spatial coordinate of the drift (GPS position), and a qualitative measurement of the habitat type obtained from the head pearl diver at the end of the drift were also recorded (Table 2). In the final two years of the project (2004 and 2005), data on depth, and visibility were also collected.

Table 1. Daily sampling protocol for piggyback spat and size-frequency sampling of *Pinctada maxima* in the Western Australian pearl oyster fishery

Drift	Objective	Tasks(s)
1	Spat sampling	Select between 50 and 250 oysters prior to cleaning and panelling. Search for spat. Record species, and/or save, label and freeze specimen for laboratory identification. Record location, date, and drift no.
2	Size-frequency sampling	Select as many animals as possible. Measure with the specifically designed measuring board, and record length-category.
3	Spat sampling	As per drift 1.
4	Spat sampling	As per drift 1
5	Size-frequency sampling	As per drift 2
6	Spat sampling	As per drift 1
7	Spat sampling	As per drift 1
8	Spat sampling	As per drift 1

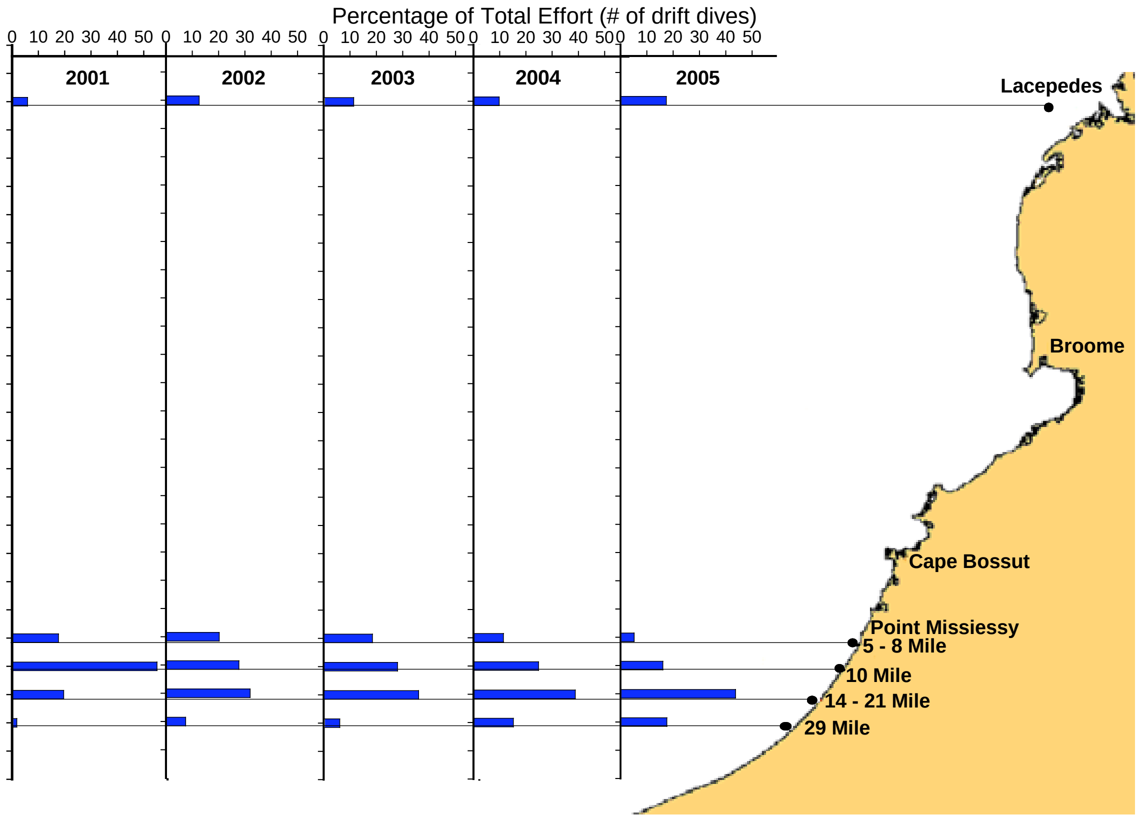


Figure 3. Distribution of sampling effort (% of drift dives) for *Pinctada maxima* spat settlement and commercial length frequency during the five years of this project.

Table 2. Habitat types and their codes used to define the main habitat composition of the *Pinctada maxima* fishery.

HABITAT TYPE	**Code**
Garden (light, medium, heavy) – *whips, sponges and coral cups*	Gn-L, Gn-M, Gn-H
Potato (light, heavy) – *lumpy ascidians*	Pt-L, Pt-H
Sand and stone – *predominantly sand and stone only*	Sd, Sd/Sn
Coral & Reef (light, mixed coral, staghorn) – *mixed means plates, brains & sand*	Cr-L, Cr-M, Cr-S
Other - e.g. seagrass	Please specify

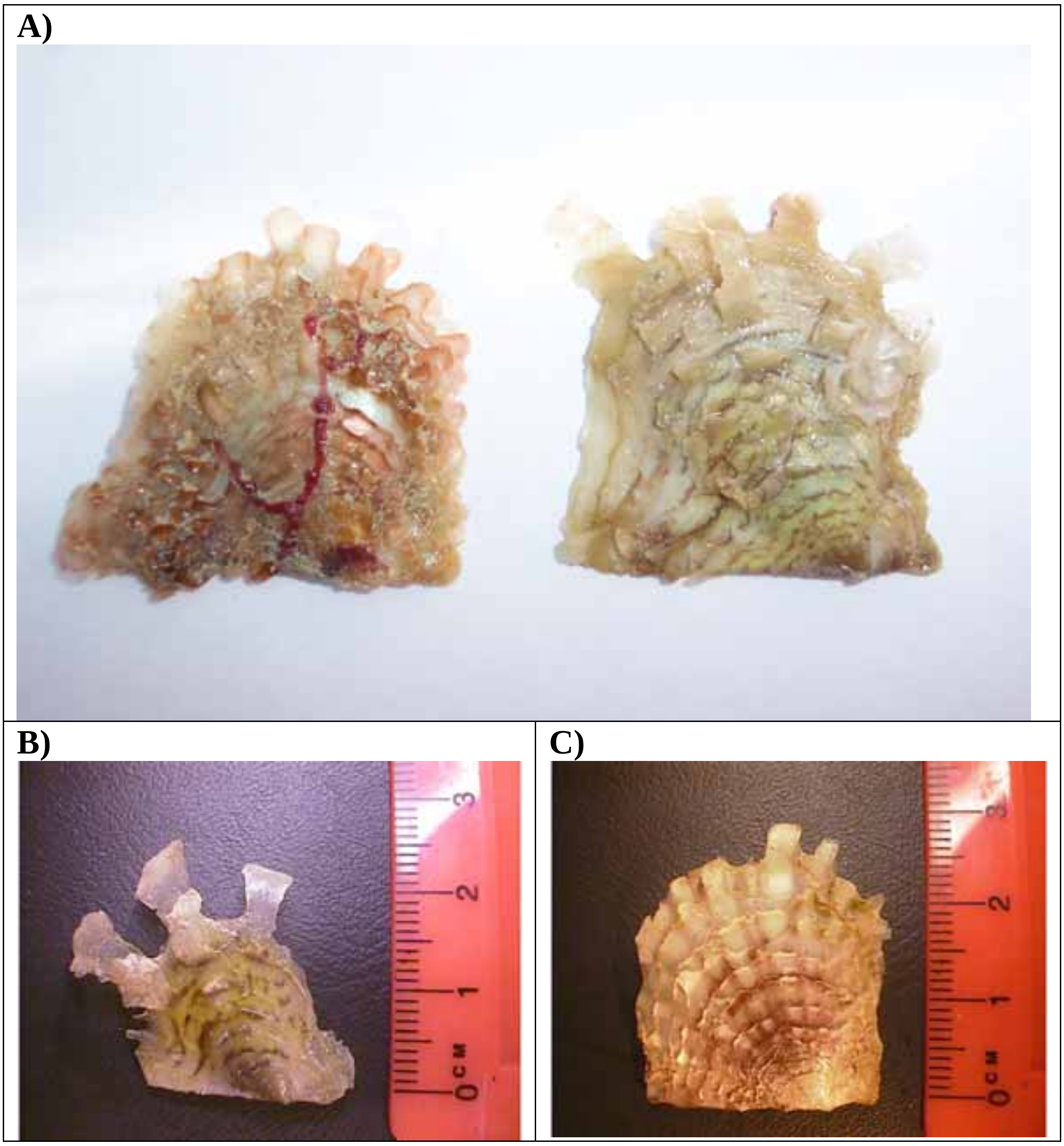


Figure 4. A comparison of the essential differences between newly settled (0+ age) *Pinctada maxima* and *Pinctada albina* found on commercially fished adult shell. A) represents a basic colour difference; Red is *P. albina*, brown/green is *P. maxima*, B) is a typical *P. maxima* with less symmetrical fingers, C) is a typical *P. albina* with a stripy appearance, and more regular shaped growth fingers.

3.1.1 Assigning age classes to piggyback spat

After examining raw length frequencies, published growth rates of spat from various *Pinctata* species and their spawning period (October - December), age-classes were assigned to the lengths obtained from each spat of *P. maxima* and *P. albina* (Table 3). These were also highly dependent on the discrete sampling period (generally March to June).

Few data on growth of *P. albina* were available, hence age-classes were assigned based on known maximum sizes (8-10 cm), spawning period (Beer, 1995), and spat growth data from other studies.

In general, natural growth of *P. maxima* on the fishing grounds is substantially slower than that recorded from the grow-out farms in the north-west of Western Australia, where the spat are subjected to optimal growing conditions (Hart and Joll, 2006). Minimum temperature on the main fishing grounds (80 Mile Beach) can be as low as 20°C (Pass et al., 1987), which is close to the minimum temperature at which *P. maxima* ceases to grow altogether ().

Table 3. Age classes assigned to each species for examination of spatio-temporal trends in settlement among different populations. Spat were collected during March-June each year. DVM – dorso-ventral measurement.

Species	DVM (mm)	Age class	Comments
Pinctada maxima	5-34.9	0+	Spat collected March-June are mostly 4-7 months
	35-74.9	1+	Spat collected are mostly 16-21 months
Pinctada albina	5-24.9	0+	Spat collected are likely to be 4-8 months
	24.9-50	1+	Spat collected are likely to be 16-22 months

3.2 Length-frequency, discard rate, and shell quality sampling.

Length-frequency sampling of the catch was undertaken following the protocol described in Table 1. A specially constructed measuring board facilitated quick measuring of the catch during the brief time available between the oyster shells being bought up on deck, graded, chipped clean, and panelled for later seeding (Figure 5). Oysters were categorised into 5mm size categories (Table 4; Figure 5), and discards (oysters graded as unsuitable because of size or quality reasons) were also measured. The date, time, and location (GPS coordinates and statistical blocks) of each drift were recorded to assist spatio-temporal analyses. Using tag-recapture data (Hart & Joll, in press), pearl oysters were assigned approximate age-classes for correlation analyses (Table 3).

Figure 5. Adult shell of a commercially harvested *Pinctada maxima* sitting atop a measuring board. For comparison, samples of 0+ and 1+ spat are also shown.

3.3 Development of a database for data storage

The spat sampling and length-frequency data were housed within a larger relational database known as the “Mollusc Minor Fishery and Biological Database”, which was developed in Microsoft Access♦. Appendix 10.3 summarises the structure of the database.

Table 4. Year class abundance indices applied to *Pinctada maxima* shells of various lengths.

Management Zone	Shell –length range	Age class
	0-35	0+
	35-75	1+
	75-105	2+
2	105-125	3+
	125-140	4+
	141-150	5+
	151-160	6+
	160+	7+
3	120-140	3+
	140-160	4+
	160+	5+

3.4 Data analysis

3.4.1 Spatio-temporal settlement analysis

Data were extracted from the database on a drift-by-drift basis and imported into a GIS program (ArcMap♦). GPS data was then categorised into 10 discrete fishing areas, or ‘pearl patches’ (Table 5). Five of the patches were fished in only one or two years and produced very little data, so were excluded from further analysis. The analysis was restricted to those five populations that were fished every year and comprise the majority (95%+) of the fishery (Table 5).

Table 5. Main pearl oyster (*Pinctada maxima*) producing areas (or pearl patches) in Western Australia. Management area refers to the zones by which TAC management is applied (see Figure 1).

Patches/Reefs	Fishing Ground	Management Zone	Populations analysed
Lacepede Patch	Lacepede Islands	3	℘
Cape Bossut	80 Mile Beach	2	
Sand Point	80 Mile Beach	2	
Compass Rose	80 Mile Beach	2	
5-8 Mile	80 Mile Beach	2	℘
10 Mile	80 Mile Beach	2	℘
14-21 Mile	80 Mile Beach	2	℘
29 Mile	80 Mile Beach	2	℘
Mandora/Red Hill	80 Mile Beach	2	
Wallal	80 Mile Beach	2	

The settlement data were examined with 2-factor ANOVA’s, after an appropriate transformation was found by examining the residuals. The equation describing the transformed index of settlement is as follows.

$$S = \log((x / y) + 0.01)$$

where S is the settlement index, x is the total number of spat found in a drift (separated into age class and species), and y is the total number of shell checked per drift. Initially, the analysis was applied to S weighted by y, but the weighting was found not to influence the overall results, and was thus not applied in the final analysis.

For the data collected by research personnel, broadscale settlement patterns were examined by Fishing Area (A) and Year (Y). These were analysed by a 2 factor ANOVA.

Least Squares means from the analyses were back-transformed to obtain settlement indices as number of spat per 1000 shell examined.

3.4.2 Depth and month analysis of settlement within populations

To further examine the interactive effects of depth, month, and year on settlement, data from two individual areas were selected out. These areas were the 10 Mile, and the 14-21 Mile pearl patches, both from the 80 Mile beach, and the most important to the fishery, producing between 60-80% of the catch each year. Depth was examined as a factor rather than a covariate, as its effect on settlement was not expected to be linear over the range of depths examined. Depth categories examined were: 9m (8-10m); 12m (11-13m); 15m (14-16m); 18m (17-19m); 21m (>20m).

3.4.3 Length-frequency analysis

Shell lengths (DVM) of *Pinctada maxima* was recorded by size-category. Variability in length frequency was analysed by chi-square and log-linear analysis. Specific effects investigated were the effects of year (2003 - 2005), method (Research vs industry personnel), and statistical area on the length frequency. Length categories examined were each 5mm category from 125 mm to 160 mm DVM. The smallest category (120-124 mm) was not included in the analysis as it was close to the legal minimum size (120 mm), and preliminary data suggested the industry was re-leasing 50% or more of these animals, perhaps due to overconservative selection.

A second test of the effect of management zone and year was also carried out using the research survey data, for which a full 5 year data set (2001-2005) was available. The interaction between various factors is tested by Chi-square marginal and partial association tests. These steps are conceptually analogous to simple and partial correlation tests.

Previous work (Hart & Joll, 2006) determined that in Zone 3 (Lacepede Islands), shells remain available to the gauntlet fishery for 2 - 3 years, whereas in Zone 2 (80 Mile beach area), shells remain available for 3 – 4 years. Based on knowledge of the principal settlement months (November, December, January), rules were assigned to shell-length data from the commercial catch, and used to generate year-class abundance indices (Table 4).

The equation used to derive abundance indices for each age class from the commercial catch is as follows

$$CPUE_i = P_i \times CPUE_{tot}$$

where $CPUE_i$ is the catch rate of age-class i, P_i is the proportion of age class i in the size-frequency sample, and $CPUE_{tot}$ is the total commercial catch rate. However, given that the project supplied only 5 years of temporal data, it was not possible to examine CPUE vs settlement data for individual age classes at this time.

3.5 Environmental and technology (GPS) effects on CPUE

A multiple regression model assessed the effect of the environment and technology, on CPUE. The response variables investigated were Zone 2 CPUE (oysters caught per diver hour) and Zone 3 CPUE. The predictor variables were GPS, measured as a “dummy variable” (years prior to GPS [1979-1993] = 0; years post GPS [1994-2004]

= 1), and the annual Southern Oscillation Index (SOI). Two components to the SOI were investigated: a) its effects on shell catchability, which equates to the SOI in Year *n*, where *n* is the fishing year of interest, and b) its effects on recruitment, which is the SOI in Year *n* - *i*, where *i* is a lag time reflecting the year in which settlement of currently fished year classes occurred. Lag times investigated were 2 to 5 years, however due to autocorrelation in the SOI indices, the effects of SOI at different lags were investigated in separate models.

3.6 Predicting future stock abundance with spat settlement data

The equation predicting stock abundance from the 1+ settlement index is expected to be of the following type. It is similar to that used for catch prediction in the Western Australian rock lobster fishery (Caputi et al., 1995).

$$CPUE_t^{125-160} = a\,S_{t-3}^{b}\,S_{t-4}^{c}$$

where $CPUE_t^{125-160}$ is the catch per unit effort of oysters in the 125 – 160 mm shell length range in year *t*, which encompasses the 4 – 6 year olds; S_{t-3}^{b} is the settlement index of 1+ spat at year *t*-3, and S_{t-4}^{c} is the *t*-4 settlement index of 1+ spat. For analysis purposes, the data is log-transformed, which results in the following linear equation.

$$\log CPUE_t^{125-160} = \log a + b\log S_{t-3} + c\log S_{t-4}$$

where *a*, *b*, and *c* are parameters of the equation, and a multiple regression analysis is used to estimate the parameters.

The assumptions of lag times will be continually updated as a longer time-series of the relationship between settlement and recruitment to the fishery is developed. Ultimately, only one or two years of settlement data may provide the predictive index, as the current hypothesis is that “spikes” in CPUE observed at irregular intervals (see Figure 17), represent the movement of one exceptional year class through the three age-classes in which the oysters remain vulnerable to exploitation.

Due to the lag-times, 2005 was the only year that had sufficient recruitment information; hence the model could not be statistically fitted to the data. However, to illustrate the methodology, these data were used to predict future CPUE. When sufficient data becomes available, the model will be properly fitted, and confidence intervals obtained for predictions.

3.7 Transport and recruitment of larvae on the North West Shelf (Scott Condie and Anthony Hart)

Larval dispersion patterns of *Pinctada maxima* were modelled by tracking particles transported by ocean currents estimated from a circulation model for the North West Shelf. Particle trajectories were used to estimate both potential settlement sites and potential spawning sites. Spawning distributions were based on a broodstock (MOP) survey conducted in September 2001 as part of FRDC Project 1998/153 (Hart and Friedman, 2004), while settlement distributions were based on three years (2001-2003) of spat survey data collected as part of this project. Analyses were restricted to the eighty Mile Beach area (Zone 2), where most of the fishery is concentrated.

3.7.1 Circulation model

The circulation model was developed as part of the North West Shelf Joint Environmental Management Study (NWSJEMS 2002, Condie et al. 2005) and was based on code referred to as MECO (Model for Estuaries and Coastal Oceans). MECO is a general-purpose finite-difference hydrodynamic model applicable to scales ranging from estuaries to ocean basins. It uses a curvilinear orthogonal grid in the horizontal and fixed 'z' coordinates in the vertical. A comprehensive description of the underlying theory is provided in the MECO Scientific Manual (Herzfeld et al. 2002). MECO has found previous applications in systems such as the Port Phillip Bay (Walker 1999), Bass Strait, the Great Australian Bight and Southeastern Australia (Bruce et al. 2001), and the Gulf of Carpentaria (Condie et al. 1999).

MECO was implemented for the NWS on a rotated latitude-longitude grid with horizontal resolution of approximately 10 km (Condie et al. 2005a). This grid extended from Cape Cuvier in the southwest to the Bonaparte Archipelago in the northeast and well beyond the shelf break (Figure 6). The vertical resolution expanded from 3 m near the surface to a maximum of 200 m at its maximum depth of 1200 m. Truncating the depth at this level had little effect on the circulation, but significantly improved computational times. The bathymetry was prescribed by spatially averaging a 30 second (0.9 km) product provided by Geosciences Australia onto the model grid. Inputs required by the model included forcing due to wind, atmospheric pressure gradients, and open boundary conditions such as temperature, salinity, and sea-level. Wind fields were taken from the NCEP-NCAR 40-year re-analysis dataset (Kalnay et al. 1996). These fields had a 12 hourly time-step and a spatial resolution of 1.8°, which were linearly interpolated onto the model time-step and model grid. The interpolated product generally showed good agreement with locally measured winds at sub-diurnal frequencies (Figure 18a). However, smaller scale processes, such as the daily sea-breeze and occasional tropical cyclones, were less adequately resolved. Winds during the major spawning period of mid October to December were predominantly from the west.

Temperature and salinity fields around the lateral boundaries of the model were interpolated from a global circulation model known as the Australian Community Ocean Model or ACOM (Schiller et al. 2000). In the absence of reliable surface fluxes, interior temperatures and salinities were modified by relaxing them towards ACOM values with a 10 day relaxation timescale. Sea-levels on the boundaries were also taken from ACOM output, with the addition of tidal constituents derived from tide gauge observations around the Cape Cuvier and Bonaparte Archipelago areas in combination with global tidal model estimates along the offshore boundaries (Eanes and Bettadpur 1995).

3.7.2 Particle dispersion and tracking

The modeled currents provided an indication of the instantaneous movements of *P. maxima* larvae in the water column. However, additional information was required to estimate advection and dispersion patterns. Individual-based particle-tracking techniques were adopted for this purpose. In the absence of any detailed information on larval swimming behavior, all particles were assumed to be non-motile and neutrally buoyant. These assumptions are relatively easy to justify in the extremely energetic environment of Eighty Mile Beach, where tidal currents and turbulent mixing velocities would normally be expected far exceed realistic larval swimming speeds (e.g. Condie 1999).

A large number (~ 105) of neutrally buoyant particles were initially seeded randomly through the water column across the model domain, with highest concentrations on the inner shelf. The circulation and particle movement calculations were then conducted simultaneously, with particle positions being updated every 10 minutes by the interpolated model current velocities. A random walk component was also added to the trajectory to represent the dispersive influence of turbulent motions not resolved by the circulation model. Each particle was individually tracked and its location recorded every three hours.

Particles followed complex paths, which were sensitive to their initial location. Individual trajectories therefore provided a very limited view of likely dispersion patterns associated with large numbers of larvae. A statistical description of the dispersion results was therefore developed from large numbers of trajectories (Condie et al. 2005b). From the spawning areas defined by the MOP data, larvae were tracked over their estimated pelagic phase of 24 to 31 days within the main spawning period of mid October to late December (Rose et al. 1990). More specifically, particles within the spawning areas (defined below) at midnight on October 15 were tracked for 24 days, after which their locations were recorded every three hours over the following 7 days. The process was then repeated starting 3 hours later (i.e. 3:00 am on October 15) and then at all subsequent 3 hourly steps until the end of the 31 day pelagic phase corresponded to December 31. To ensure that the results were not unduly dominated by those particles remaining within spawning areas for extended periods, each particle was only permitted to initiate a new trajectory 7 days after it had initiated the last one.

The combination of all recorded locations provided the final estimate of potential settlement distribution. This differs from an estimate of actual settlement, which would require additional factors such as habitat distribution, habitat preference, and larval mortality to be taken into account. The approach taken to estimate spawning areas defined by the spat data was the same as that described above, except that trajectories were tracked back in time. Results were obtained for all modeled years

(1994-1999) which were further amalgamated into an average distribution over the entire five year modeling period.

3.7.3 Biological surveys

A pearl oyster stock survey conducted in September 2001 revealed that distributions are largely limited by habitat availability (Hart and Friedman 2004). This finding, combined with the longevity of the large broodstock (or MOP) (Rose et al. 1990), suggests that distributions are likely to be relatively stable and hence that the 2001 MOP distributions represented an acceptable proxy for the modeling period (1994-1999). A measure of the relative abundance of MOP was based on the average number of shell collected for each hour the vessel drifted within the target populations (Hart and Friedman 2004).

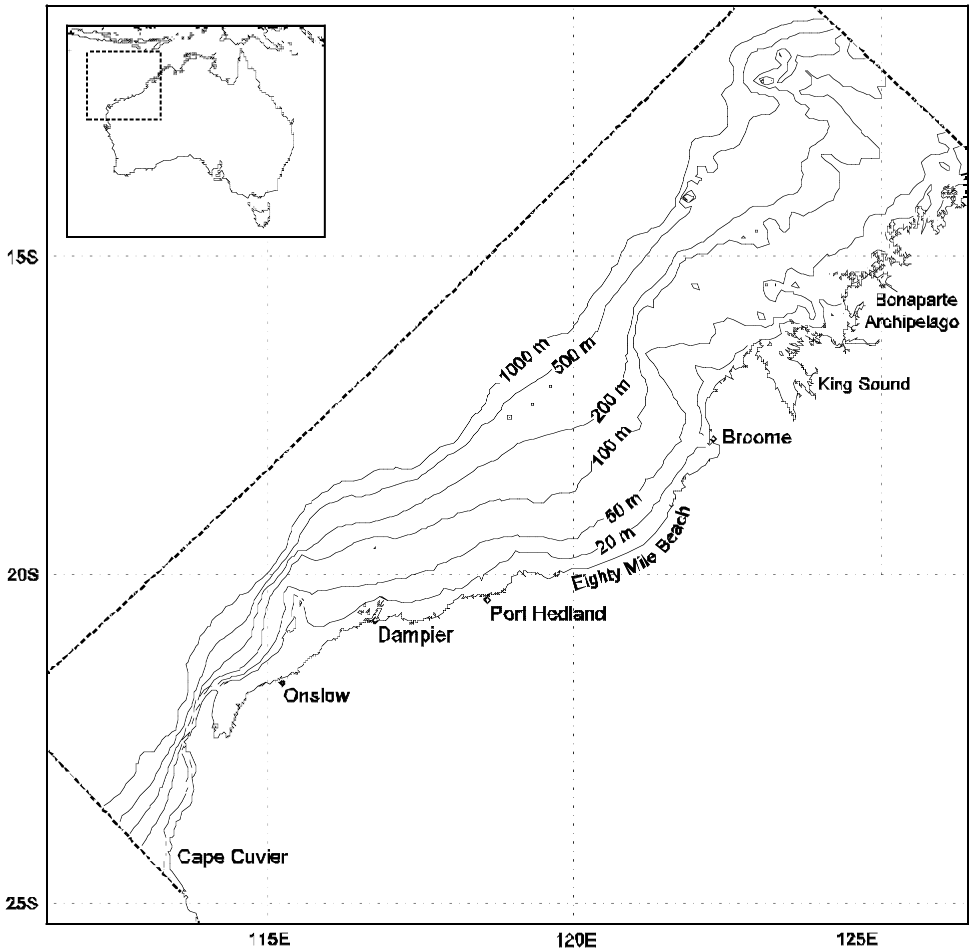


Figure 6. Map of the model grid region, bathymetry, and key locations used in the circulation modelling.

Data from piggyback spat surveys undertaken during the first three-year period of the project (2001-2003) were used. Results indicated a sufficient consistency of settlement patterns within these years to warrant combining them into a single estimate of settlement distribution. Average number of spat per shell within a 10 nm grid cell therefore provided a measure of spat relative abundance. Information on the spat year classes were not required for the current analysis.

4 Results and Discussion

4.1 Sampling protocols and data storage for piggyback spat and length-frequency data

The sampling protocols resulted in over 598,000 shells sampled for measurement of piggyback spat over the 5 sampling years of the project. The sampling proportion in terms of percent coverage (of total catch) varied from 18% to 31% (Table 6). Preliminary sampling was also carried out in 2000 by the pearling industry prior to the commencement of the project to facilitate data collection protocols.

Table 6. Commercially caught *Pinctada maxima* shell examined for the presence of 0+ and 1+ . *maxima* and *P. albina* spat, and measured for length-frequency, from 2001 to 2005.

Year	No. shell examined for spat	% coverage (of total catch)	No. shell measured for length-frequency	% coverage (of total catch)
2001	138,000	20	12,900	2
2002	101,600	18	7,900	2
2003	119,300	25	40,600	8
2004	127,700	31	30,000	7
2005	111,700	23	25,800	5
TOTAL	598,300		117,200	

Breaking up the sampling effort between dedicated research personnel and industry personnel, the research personnel carried out the majority (> 80%) of the sampling each year (Table 7). Two dedicated observers on different vessels achieved this during each fishing period (neaps), whereas the industry personnel had to undertake spat and length sampling after completing their normal duties. Structuring the sampling scheme around the daily drift schedule in 2003 to 2005, rather than around the neap schedule, as occurred in 2001-2002, showed a beneficial improvement in level of coverage by industry observers (Table 7).

Data were stored in a Microsoft Access Database built especially for the sampling protocol. Details are supplied in Appendix 10.

Table 7. Commercially caught *Pinctada maxima* shell examined by dedicated research observers (Research) and industry personnel (Industry) for the presence of 0+ and 1+ *P. maxima* and *P. albina* spat, and measured for length-frequency, from 2001 to 2005.

Year	Data Type	Shell examined for spat	Shell measured for length-frequency
2001	Research	113,700	12,900
	Industry	24,300	0
2002	Research	93,400	7,900
	Industry	8,200	0
2003	Research	86,500	28,300
	Industry	32,800	12,300
2004	Research	109,200	25,600
	Industry	18,500	4,400
2005	Research	94,800	20,300
	Industry	16,900	5,500

4.2 Spatio-temporal trends in spat abundance

4.2.1 0+ age-class (Pinctada maxima)

Abundance of 0+ age class *Pinctada maxima* differed significantly between years, however there was a significant interaction between year and area, indicating that temporal trends were area specific (Table 8, Figure 7).

For example, in 2001, average abundance was not significantly different across all populations, however in 2002, two areas (5-8 Mile; 14-21 Mile) were significantly higher in abundance of 0+ *P. maxima spat*, than the others (Figure 7). A similar effect occurred in 2003; with two areas having a higher abundance of 0+ spat then the others, although a different two from the previous year (Figure 7). In 2004, there was no significant difference between any of the areas. In 2005, there was an exceptional increase in abundance in the three areas comprising the centre of the fishery (5-8 Mile; 10 Mile; 14-21 Mile), but not at the Lacepede Islands or the 29 Mile, which are north and south respectively, of the main fishery (Figure 7).

4.2.2 0+ age-class (Pinctada albina)

Abundance of 0+ age class *Pinctada albina* differed significantly between years, however there was a significant interaction between year and area, indicating that temporal trends were area specific (Table 8).

For example, in 2001, average abundance was higher in two areas (10 Mile, 14-21 Mile), compared to the Lacepede Islands and the 5-8 Mile (Figure 8). In 2002, the 29 Mile population had the highest settlement of *P. albina*, followed by 10 and 14-21 Mile, with the 5-8 Mile again having the lowest settlement. In general, settlement of

0+ *P. albina* varied from year to year in all areas, although some locations (e.g. 5-8 Mile) experience a larger variation than others (e.g. 14-21 Mile; Figure 8).

Table 8. ANOVA results for the effect of Year and area (pearl patch) on abundance of 0+ *Pinctada maxima* (5 – 34 mm DVM) and *P. albina* (5-24 mm DVM) in wild stocks. Data collected by researchers only

	Pinctada maxima				*Pinctada albina*			
	d.f	MS	F	*p*	d.f	MS	F	*p*
Year	4	34.2	168	<0.001	4	15.3	46.5	<0.001
Area	4	12.8	62.7	<0.001	4	42.4	129.3	<0.001
Year × Area	16	9.1	44.6	<0.001	16	6.8	20.8	<0.001
Residual	2851	0.2			2847	0.33		

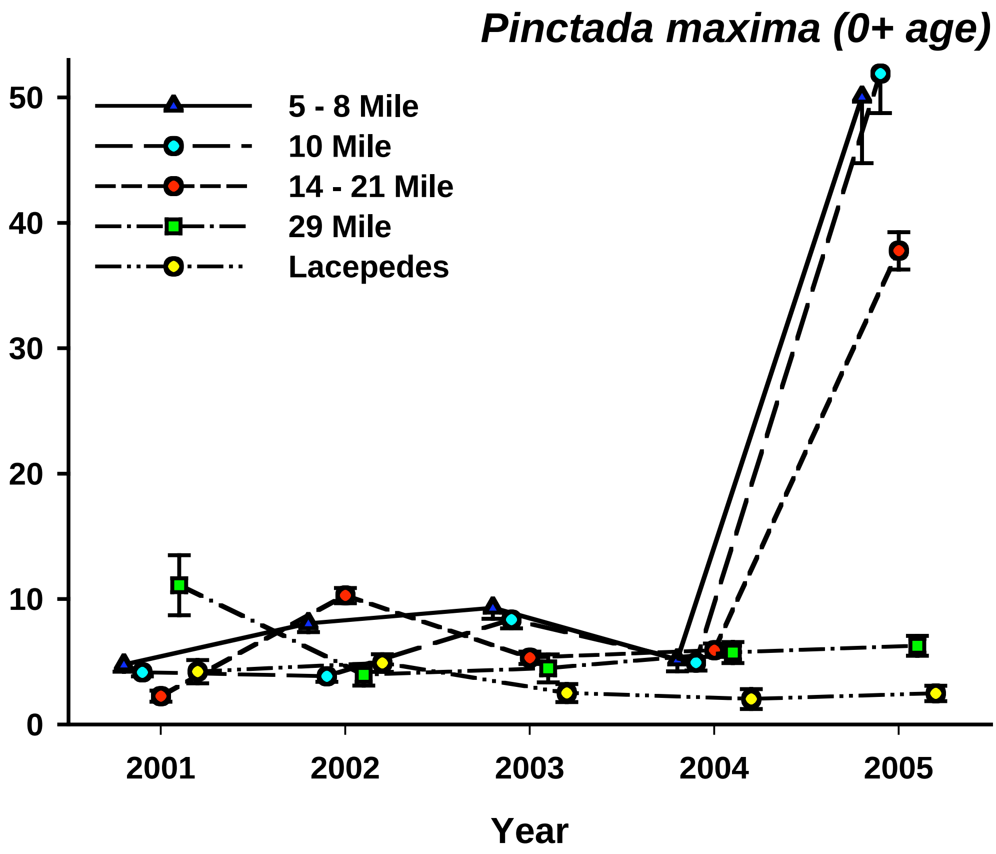


Figure 7. Spatio-temporal trends in the abundance of 0+ *Pinctada maxima* (5-34 mm DVM) at the five areas comprising the majority of the commercially fished wild stocks in Western Australia. Error bars are SE, and data are from research personnel only.

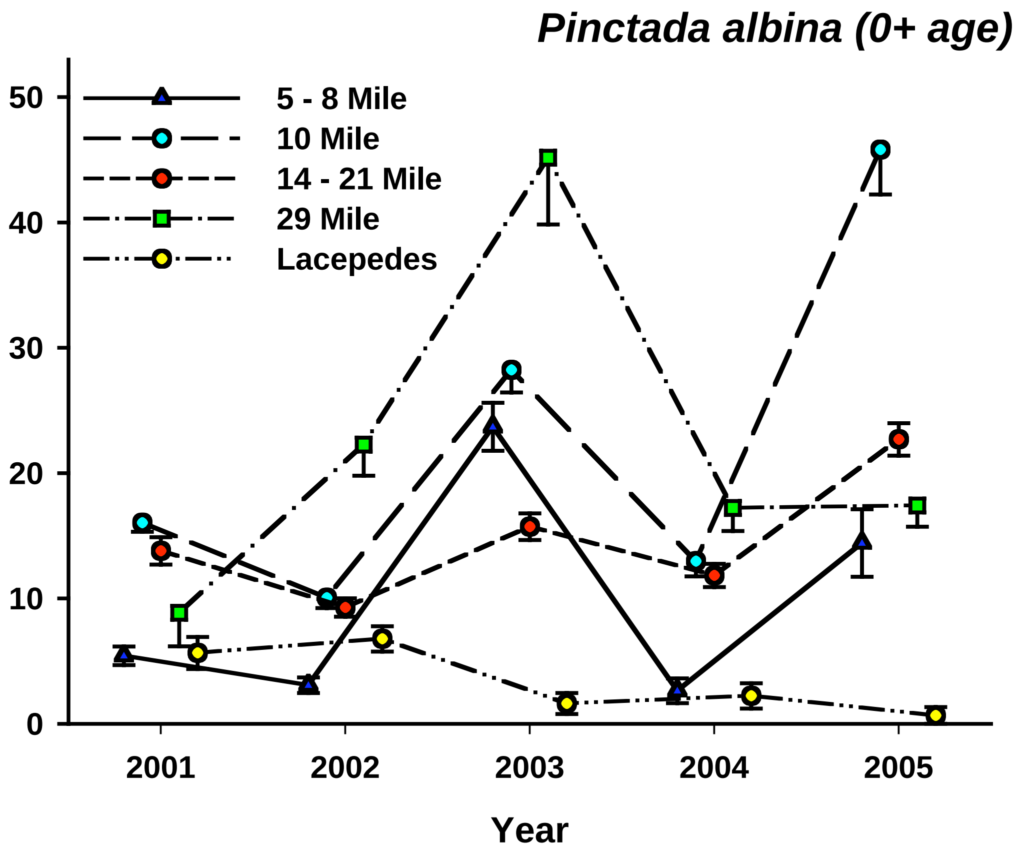


Figure 8. Spatio-temporal trends in the abundance of 0+ *Pinctada albina* (5-24 mm DVM) at five areas in Western Australia. Error bars are SE, and data are from research personnel only.

4.2.3 1+ age-class (Pinctada maxima)

Abundance of 1+ age class *Pinctada maxima* differed significantly between years, however there was a significant interaction between year and area, indicating that temporal trends were area specific (Table 9).

For example, in 2001, average abundance was not significantly different across all areas, however in 2002 the Lacepede Islands had a significant higher abundance of 1+ *P. maxima* than any other area (Figure 9). In 2003 there was a larger variation in settlement, with the Lacepedes and 14-21 Mile having a significantly higher 1+ abundance than 5-8 Mile and 29 Mile. In 2004, some of these patterns were reversed, with the 5-8 Mile Patch having a significantly higher abundance of 0+ than the Lacepede Islands. In 2005, the Lacepde Islands decline again in 1+ abundance.

Overall, the Lacepede Islands showed the largest temporal variability in abundance of 1+ *Pinctada maxima*, while the 29 Mile and 10 Mile areas showed the lowest variability (Figure 9).

Table 9. ANOVA results for the effect of Year and Area on abundance of 1+ *Pinctada maxima* (35 – 74 mm DVM) and *P. albina* (25-50 mm DVM) in wild stocks. Date used were log transformed (x + 0.01) abundance

	Pinctada maxima				*Pinctada albina*			
	d.f	MS	F	*p*	d.f	MS	F	*p*
Year	4	0.49	2.8	0.03	4	35.76	142.5	<0.001
Area	4	2.04	11.8	<0.01	4	36.5	145.4	<0.001
Year × Area	16	2.06	11.9	<0.01	16	10.86	43.3	<0.001
Residual	2847	0.17			2847	0.25		

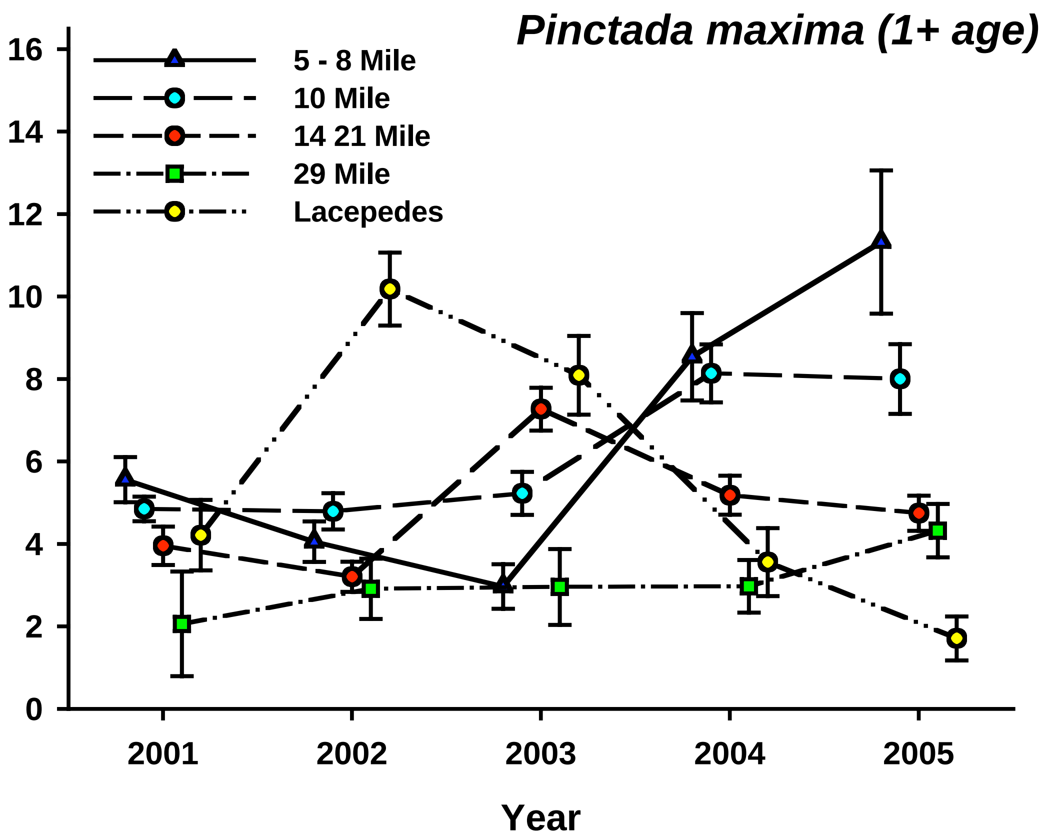


Figure 9. Spatio-temporal trends in the abundance of 1+ *Pinctada maxima* (35-74 mm DVM) at the five areas comprising the majority of the commercially fished wild stocks in Western Australia. Error bars are SE, and data are from research personnel only.

4.2.4 1+ age-class (Pinctada albina)

Abundance of 1+ age class *Pinctada albina* differed significantly between years, however there was a significant interaction between year and area, indicating that temporal trends were area specific (Table 9).

Figure 10 shows the overall trends in abundance of age 1+ *P. albina* at the main pearl oyster areas. Temporal trends differed between areas. Abundances of 1+ *P. albina* were stable over time at the Lacepede Islands, oscillated substantially at the 5-8 Mile patch, and increased at the 10 Mile and 14-21 Mile patches (Figure 10).

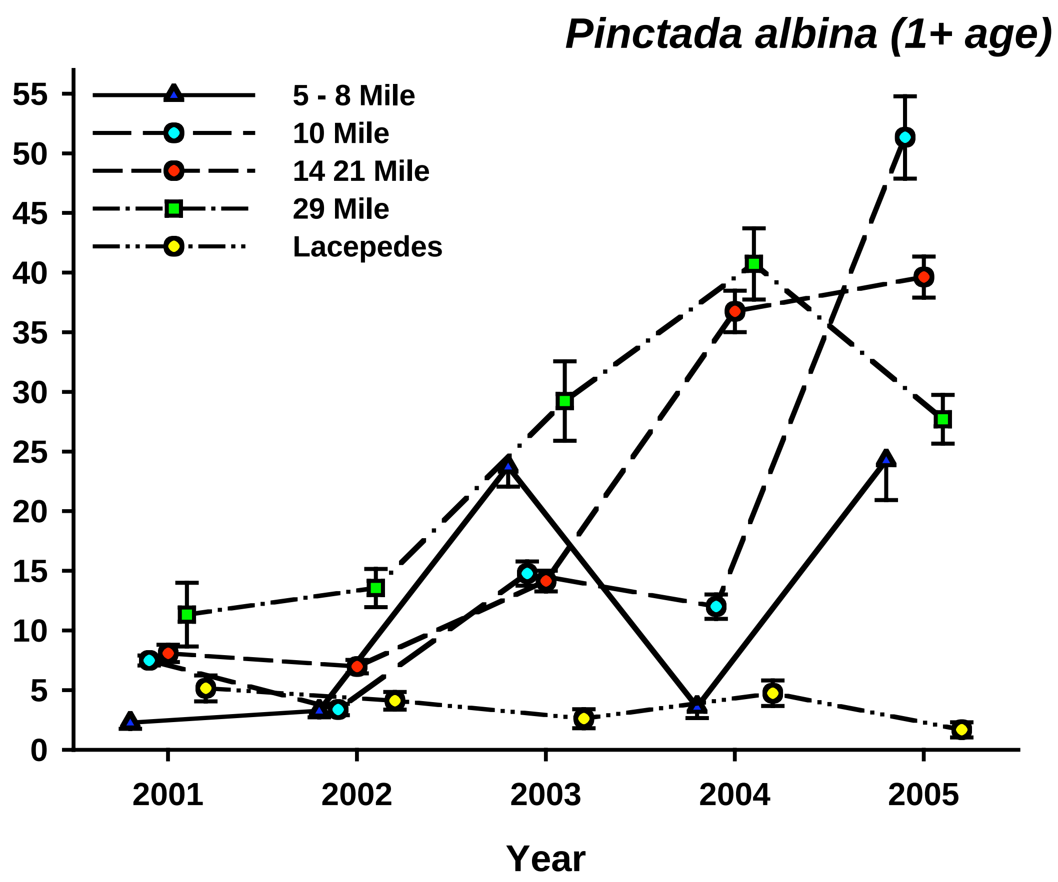


Figure 10. Spatio-temporal trends in the abundance of 1+ *Pinctada albina* (25-50 mm DVM) at five populations in Western Australia. Error bars are SE, and data are from research personnel only.

4.2.5 Effect of month on settlement patterns (80 Mile Beach)

Four fishing areas on the 80 Mile Beach fishing grounds were examined further for the interactive effects of Month (March, April, May, June), Year, and area on settlement. There was a higher order significant interaction between Year, and Month, and area for 0+ *Pinctada maxima*, indicating that trends in spat abundance over years were area and month specific (Table 10). A similar result was obtained for 1+ *P. maxima* (Table 10).

The clear increase in the 2005 settlement of 0+ *P. maxima* is consistent in the three areas it occurred, regardless of month (Figure 11), although in the 14-21 Mile patch, abundance in June did decline close to pre-2005 levels. Despite this anomaly, the 14-21 Mile patch had the most consistent settlement within a year, but varied between years in comparison to the 10 Mile pearl patch (Figure 11).

Considering individual areas for abundance of 1+ *P. maxima*, some trends are noteworthy. In the 10 Mile patch, between month abundance is generally consistent within a given year, with the exception of 2005, where it increased significantly between April and June (Figure 12). In the 14-21 Mile patch, between year differences in spat abundance were greater than the within-year (between-months) variation. There is a suggestion however, of a slightly increasing trend from April to June. Variability in abundance of 1+ *P. maxima* was generally greater in the smaller patches off 80 Mile Beach (5-8 Mile; 29 Mile; Figure 12), mostly due to smaller sample sizes.

Table 10. The effect of Year, Month, and Patch, on the abundance of 0+ spat and 1+ spat of *Pinctada maxima* in wild stocks in Western Australia

	0+ Pinctada maxima				***1+ Pinctada maxima***			
	d.f	MS	F	*p*	d.f	MS	F	*p*
Year	4	75	313	<0.001	4	2.33	13.1	<0.001
Month	3	2.49	10.4	<0.001	3	0.75	4.21	0.006
Area	3	11.9	16.3	<0.001	3	2.56	14.5	<0.001
Year × Month	3	0.90	4.46	0.004	3	0.33	1.97	0.117
Year × Area	6	4.70	23.2	0	6	1.10	6.60	0.000
Month × Area	2	1.33	6.55	0.001	2	0.00	0.01	0.996
Year × Month × Area	17	0.99	4.89	0	17	0.36	2.16	0.003
Residual	2116	0.20			2113	0.17		

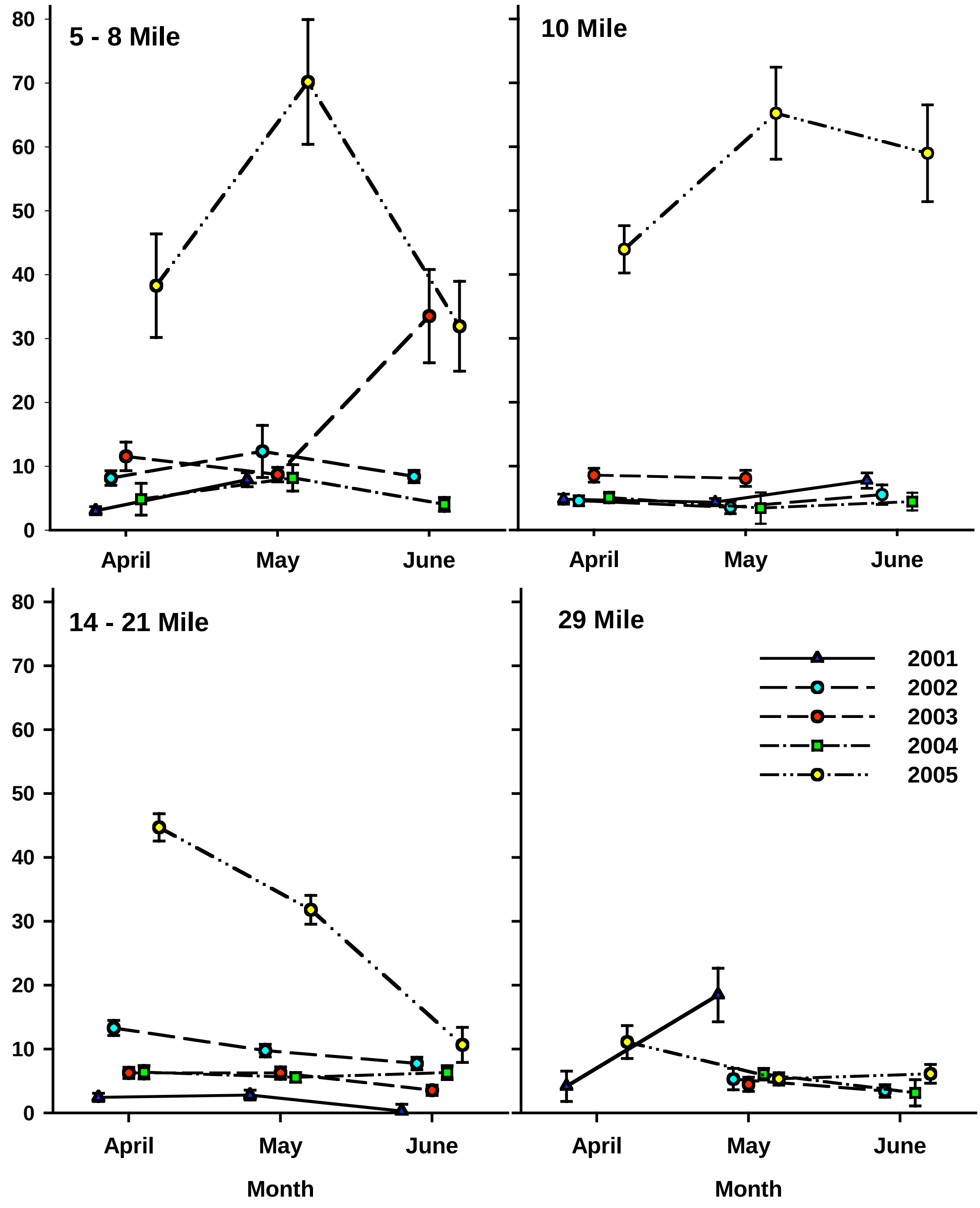


Figure 11. Varibility in settlement of 0+ *Pinctada maxima* (5-34 mm DVM) at the four areas (pearl patches) on 80 Mile Beach (Zone 2) that comprise the majority of the commercially fished wild stocks in Western Australia. Error bars are SE, and data are from research personnel only.

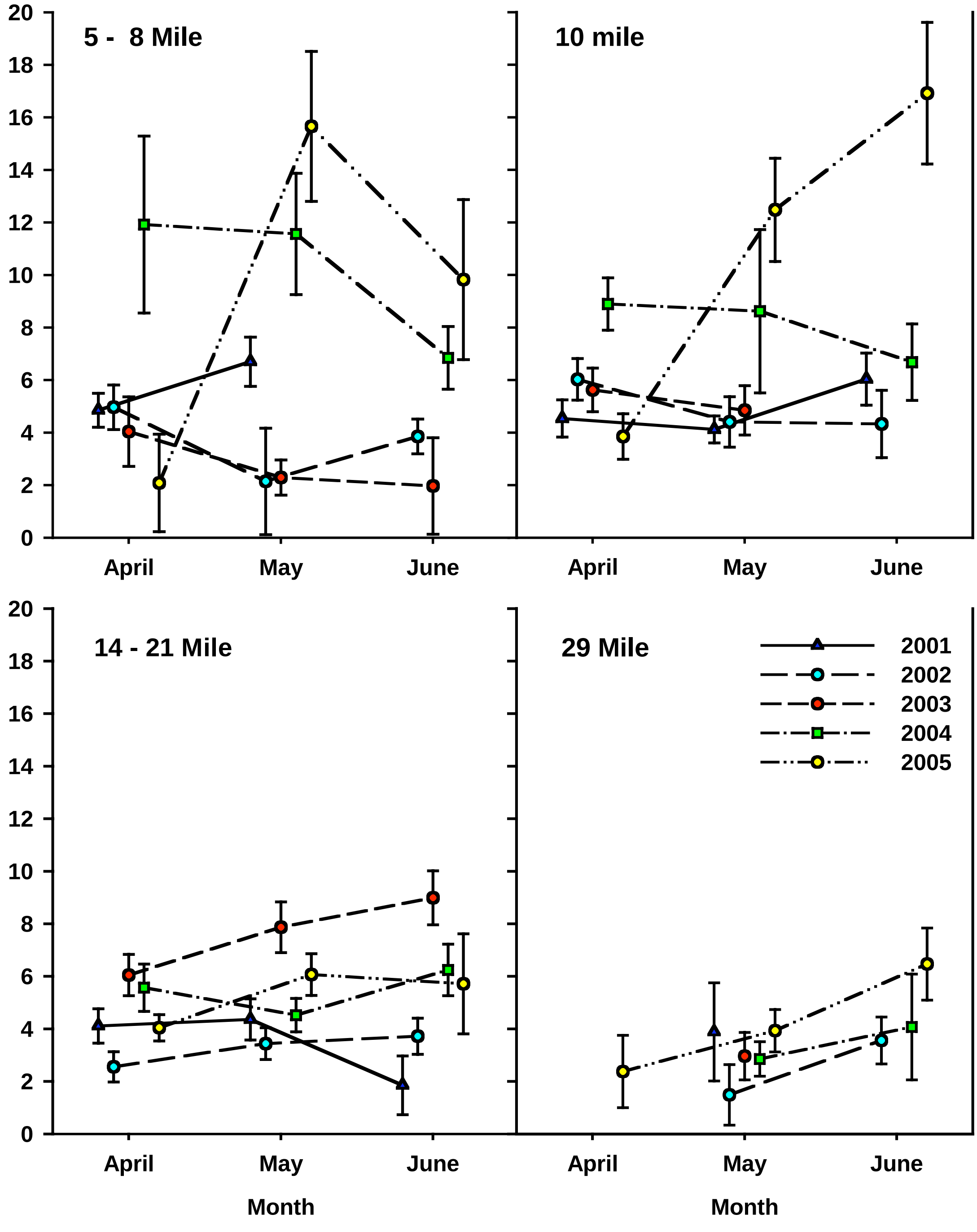


Figure 12. Varibility in settlement of 1+ *Pinctada maxima* (35-74 mm DVM) at the four areas (pearl patches) on 80 Mile Beach (Zone 2) that comprise the majority of the commercially fished wild stocks in Western Australia. Error bars are SE, and data are from research personnel only.

4.2.6 Effect of depth on settlement patterns

Settlement patterns were examined to assess what component of the significant month effect was depth related. Analyses were restricted to 0+ *Pinctada maxima* as this contained the clearest signal in the data over the two years for which depth data was collected. In this analysis, year was treated as a random factor.

There was a higher order significant interaction between Year, and Month, and Depth for 0+ *Pinctada maxima*, indicating that trends in spat abundance over time were depth and month specific (Table 11).

The increase in abundance of 0+ *P. maxima* in 2005 was restricted to the 9 – 15m depth categories, but not in deeper stocks (Figure 13). This tends to suggest that it was the more inshore, shallow areas that received the increased settlement, which agrees with the Area x year analysis (see Table 8).

Table 11. The effect of Year (2004 and 2005), Month (April, May, June), and Depth, on the abundance of 0+ spat of *Pinctada maxima* in wild stocks in Western Australia

Source of variation	d.f. Effect	MS Effect	d.f. Error	MS Error	p
Month	4	16.7	4.5	7.03	0.19
Depth	5	4.8	5.8	5.07	0.52
Year	1	118.2	5.59	13.4	0.03
Month × Depth	13	0.51	10.5	0.99	0.88
Month × Year	4	3.98	8.3	1.91	0.17
Depth ×Year	5	3.00	6.1	0.86	0.08
Month × Depth ×Year	5	1.08	812	0.29	0.002

4.2.7 Correlations in settlement among areas.

There was a significant positive correlation in settlement of age 0+ *Pinctada maxima* between the three areas at the centre of the fishery (5-8 Mile; 10 Mile; 14-21 Mile; see Table 12), however these correlations were strongly influenced by the 2005 settlement. For those populations further apart, correlations between settlement were not significant. A similar trend was seen for the 0+ age class of *P. albina*, although only one correlation (10 Mile vs 14-21 Mile) was statistically significant due to the small sample sizes (Table 12). The addition of a longer time series of data is likely to consolidate the observed trends.

Data from the 1+ age class verified the correlations of the 0+ age class, however the strength of the correlations were generally weaker (Table 12). For example, the only significantly positive correlation for *P. maxima* was that observed between the 10 Mile and 14-21 Mile areas. Also, in the case of both *P. maxima*, and *P. albina*, there was a significantly negative correlation between 1+ abundance in the Lacepede Islands and the 5-8 Mile area. This may be due to environmental effects on spatial distribution of recruitment.

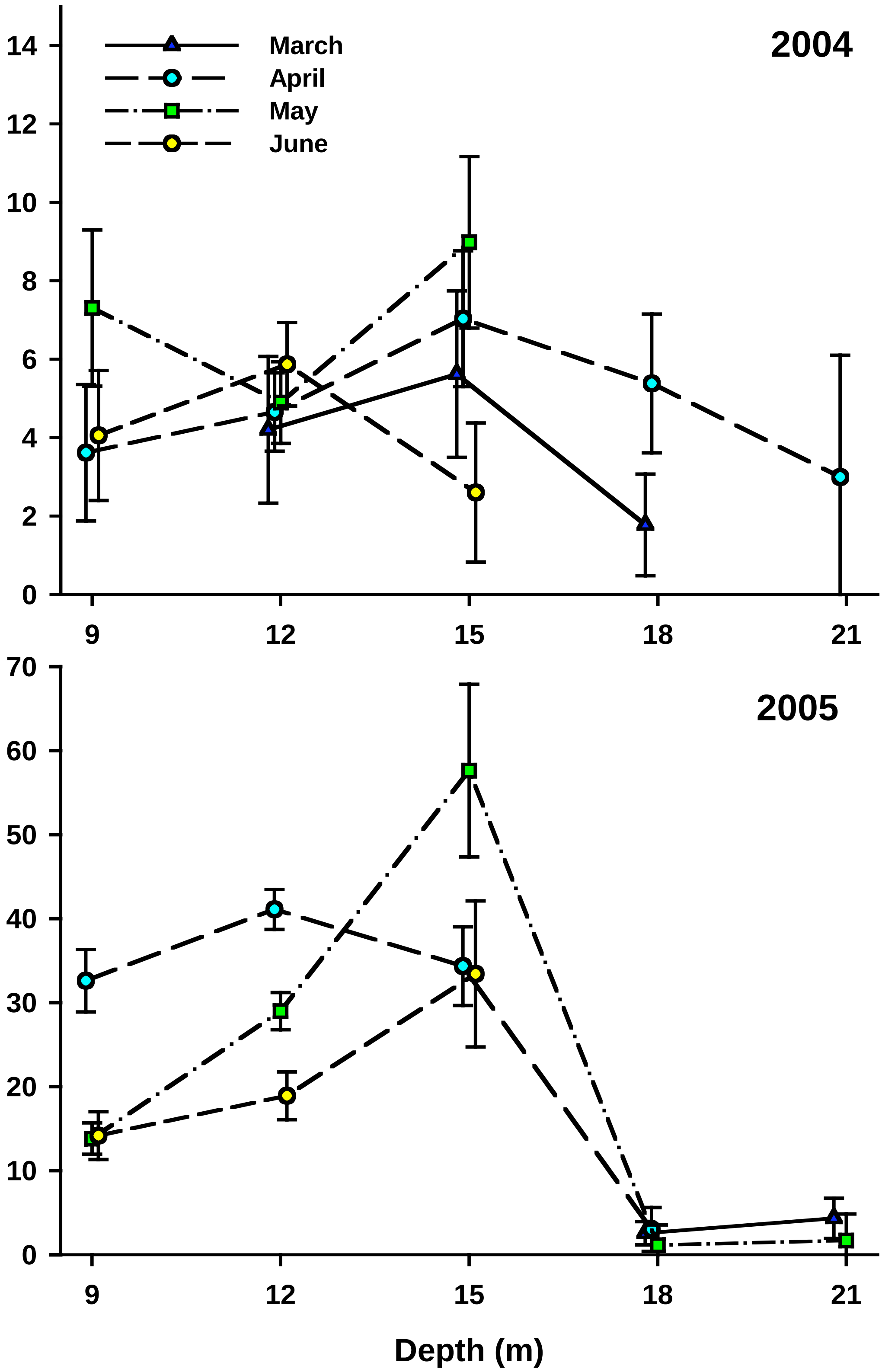


Figure 13. Variability in settlement of 0+ *Pinctada maxima* (5-34 mm DVM) by depth and month over the years 2004 and 2005. Error bars are SE, and data are from research personnel only.

Table 12. Correlation coefficients (*r*) of 0+ and 1+ settlement patterns of *Pinctada maxima* and *P. albina* between fishing areas over the years 2001 to 2005. Values in bold are significant at $v = 3$, 2-tailed test. Data used were mean standardised abundance for each year.

	Pinctada maxima				*Pinctada albina*			
	5-8 Mile	10 Mile	14-21 Mile	29 Mile	5-8 Mile	10 Mile	14-21 Mile	29 Mile
0+ age class								
Lacepede Islands	-0.32	-0.43	-0.24	0.16	-0.67	-0.8	-0.78	-0.37
5-8 Mile		**0.99**	**0.96**	-0.12		0.82	0.71	0.65
10 Mile			**0.92**	-0.3			**0.98**	0.23
14-21 Mile				-0.27				0.04
1+ age class								
Lacepede Islands	**-0.91**	-0.79	-0.04	-0.41	**-0.95**	-0.82	-0.44	-0.36
5-8 Mile		**0.88**	-0.16	0.62		0.78	0.42	0.45
10 Mile			0.2	0.68			0.77	0.51
14-21 Mile				0.18				0.84

4.2.8 Correlation in settlement patterns between species.

Data reflecting the correlation of settlement between species were generally ambiguous and equivocal. For example, there was a significant positive correlation between abundance of 0+ *Pinctada maxima* and *P. albina* in the Lacepede Islands, but no correlation for the 1+ spat (Table 13). The exception appears to be the 10 Mile area, which recorded a significant positive correlation of 0+ spat abundance between the species, and a high (but non-significant) correlation for 1+ spat (Table 13). These results suggest that the evidence supporting the use of *Pinctada albina* as a 'surrogate' or additional settlement index to *P. maxima* is not particularly strong, although it may be useful in certain areas such as the 10 Mile pearl patch.

Table 13. Correlation coefficients (*r*) of settlement patterns between *Pinctada maxima* and *P. albina* for 0+ and 1+ age classes in each area. Values in bold are significant at $v = 3$. Data used were mean standardised abundance for each year (2001 to 2005).

0+ age class					1+ age class				
Lac. Island	5-8 Mile	10 Mile	14-21 Mile	29 Mile	Lac. Island	5-8 Mile	10 Mile	14-21 Mile	29 Mile
0.92	0.48	**0.90**	0.66	-0.79	0.21	0.13	0.70	0.34	0.52

4.3 Correlations between abundance of 0+ and 1+ *Pinctada maxima*

4.3.1 All Areas

In Zone 2 (80 Mile Beach) there was a positive correlation between 0+ spat abundance and 1+ spat abundance one year later for the industry data (n = 5; r = 0.68), and the research data (n = 4; r = 0.74). In Zone 3 (Lacepede Islands), only research data was available. There was a significantly positive correlation (r = 0.93; Table 14) between 0+ spat (Year n), and 1+ spat (Year n + 1).

4.3.2 By Fishing Area (Pearl Patch or Reef)

The research data was further delineated by major fishing areas, however there was not sufficient industry data to permit analysis at this scale. A significant positive correlation between 0+ and 1+ spat abundance occurred for the 14-21 mile (Table 14), and a high positive correlation occurred for the 10 Mile area (Table 14). No clear relationship was evident in the other areas (Table 14).

Table 14. Correlation coefficients (*r*) of settlement patterns between 0+ *Pinctada maxima* at Year *n*, and 1+ *P. maxima* at Year *n* + 1, in the main fishing areas. Values in bold are significant at *v* = 3, 2-tailed test. Data used were mean standardised abundance for each year (2001 to 2005).

Area	Lacepede Islands	5-8 Mile	10 Mile	14-21 Mile	29 Mile	80 Mile Beach (Overall)
r	**0.93**	-0.07	0.76	**0.98**	-0.12	0.68

The inconsistency in the correlation between sequential year abundances of cohorts from different fishing patches is unexplained at this point, but may be related to insufficient sampling, and patchy settlement. During the project, the Lacepde Islands, 10 Mile, and 14-21 Mile stocks received 75 – 80% of all sampling, which reflected the fishing patterns of the industry. These were the stocks for which year class correlations of spat abundance were strongest.

4.4 Length-frequency of *Pinctada maxima*

4.4.1 The effect of time, spatial area, and methodology

There was an interaction between size-class and method and size-class, method and time (Table 15), indicating that research and industry personnel were obtaining similar measurements of the size-frequency of *P. maxima*, but it was not consistent over time or spatial area (Figure 14). In Grid 4355 (mostly the 10 Mile Pearl Patch; see Table 5 for description of pearl patches), there was general agreement between methods over all years, with the exception of the 125-130 mm size class (Figure 14). Either it is being over-sampled by research personnel, or under sampled by industry personnel. In Grid 4454 (mostly the 10 Mile Pearl Patch), this disparity in size-class representation is more evident between the two sampling methods (Figure 14). Reasons for this are not clear, it may be due to overly conservative selection of animals near the legal minimum length by pearl companies. However it may be inconsistency of sampling with respect to discards. The sampling protocol is to sample before discard shell have been identified, but this may have been occurring on a routine basis. This will be clarified in the 2006 sampling season.

4.4.2 The effect of time and management area

Clear differences in length-frequency over time were found in Zone 3, in comparison with Zone 2, as revealed by the significant interactions between size-class and year, and size-class and area (Table 16). Length-frequencies in Zone 2 were stable in distribution over time, compared to Zone 3 where the mode oscillated up and down, presumably reflecting year class strengths (Figure 15). This is most likely an effect of irregular recruitment in Zone 3, compared to Zone 2. Support for this hypothesis is found by statistically comparing the variability of mean 1+ settlement rate in Zone 2 and Zone 3 over the years 2001 to 2004, and 1992 to 1995 (Data from an earlier study of Joll, 1996). There was a significantly higher variability in 1+ settlement in Zone 3 (s^2 = 17.5), compared to Zone 2 (s^2 = 1.2) (F = 0.07; p < 0.01).

Table 15. Log-linear modelling results for the effects of year (2003-2005), spatial area (Grids 4355 vs 4454), and method (Industry vs Research Sampling) on the length-frequency distribution of the commercial catch of *Pinctada maxima*. Only the higher order interactions of importance are presented. *P* is the probability of the null hypothesis, which is that the variables are independent of each other.

Variable	d.f.	Partial Association	*p*	Marginal Association	*p*
Size-class × Method	6	197	< 0.001	262	< 0.001
Size-class × Method × Year	12	38.9	< 0.001	47.0	< 0.001
Size-class × Method × Grid	6	11.0	0.09	14.0	0.03

Table 16. Log-linear modelling results for the effects of year (2001-2005), and management area (Zone 2 vs Zone 3) on the length-frequency distribution of the commercial catch of *Pinctada maxima*. Research sampling dataset only. Only the higher order interactions of importance are presented. *P* is the probability of the null hypothesis, which is that the variables are independent of each other.

Variable	d.f.	Partial Association	*p*	Marginal Association	*p*
Size-class × Area	7	1400	< 0.001	1451	< 0.001
Size-class × Year	28	208	< 0.001	249	< 0.001

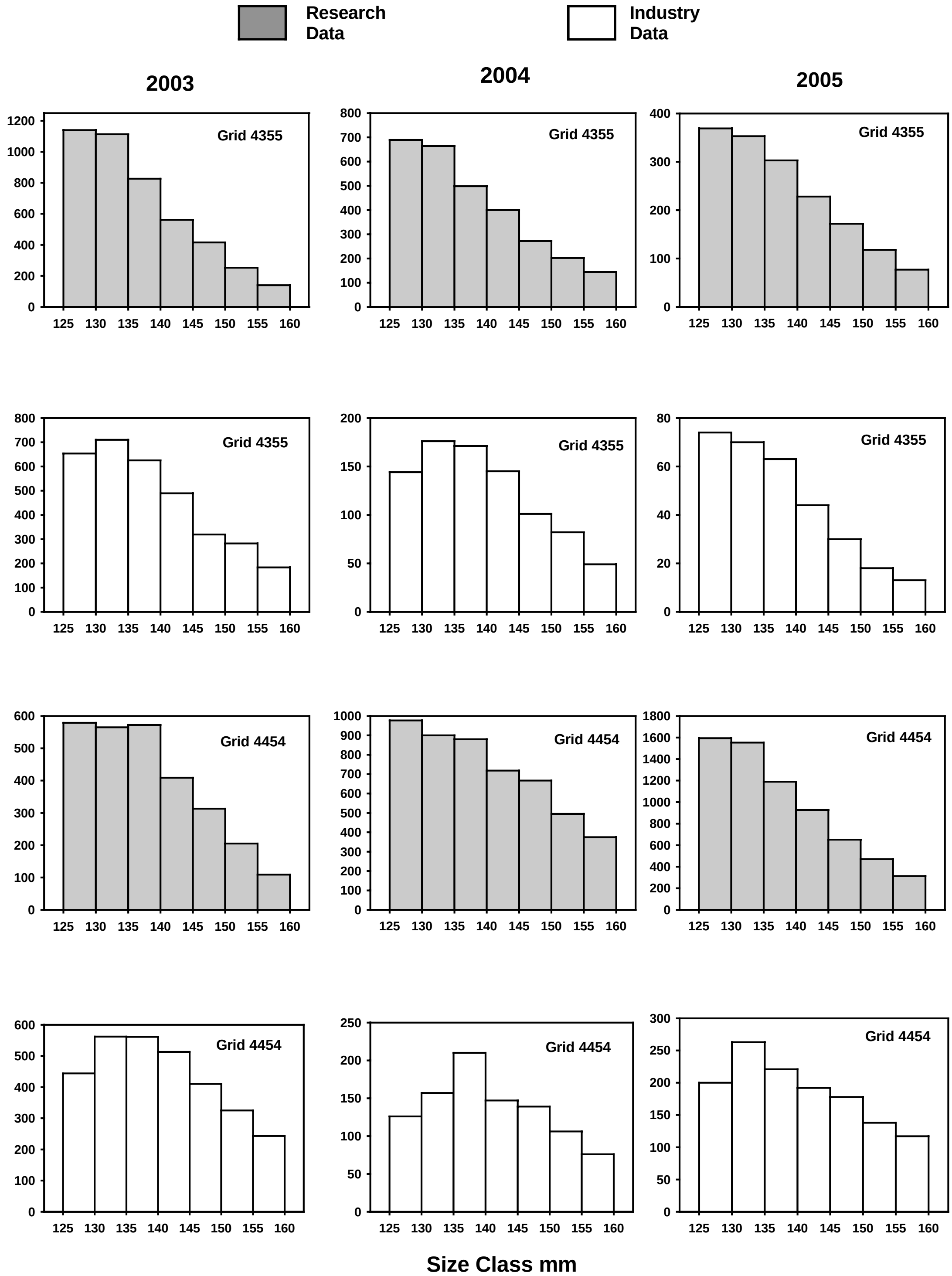
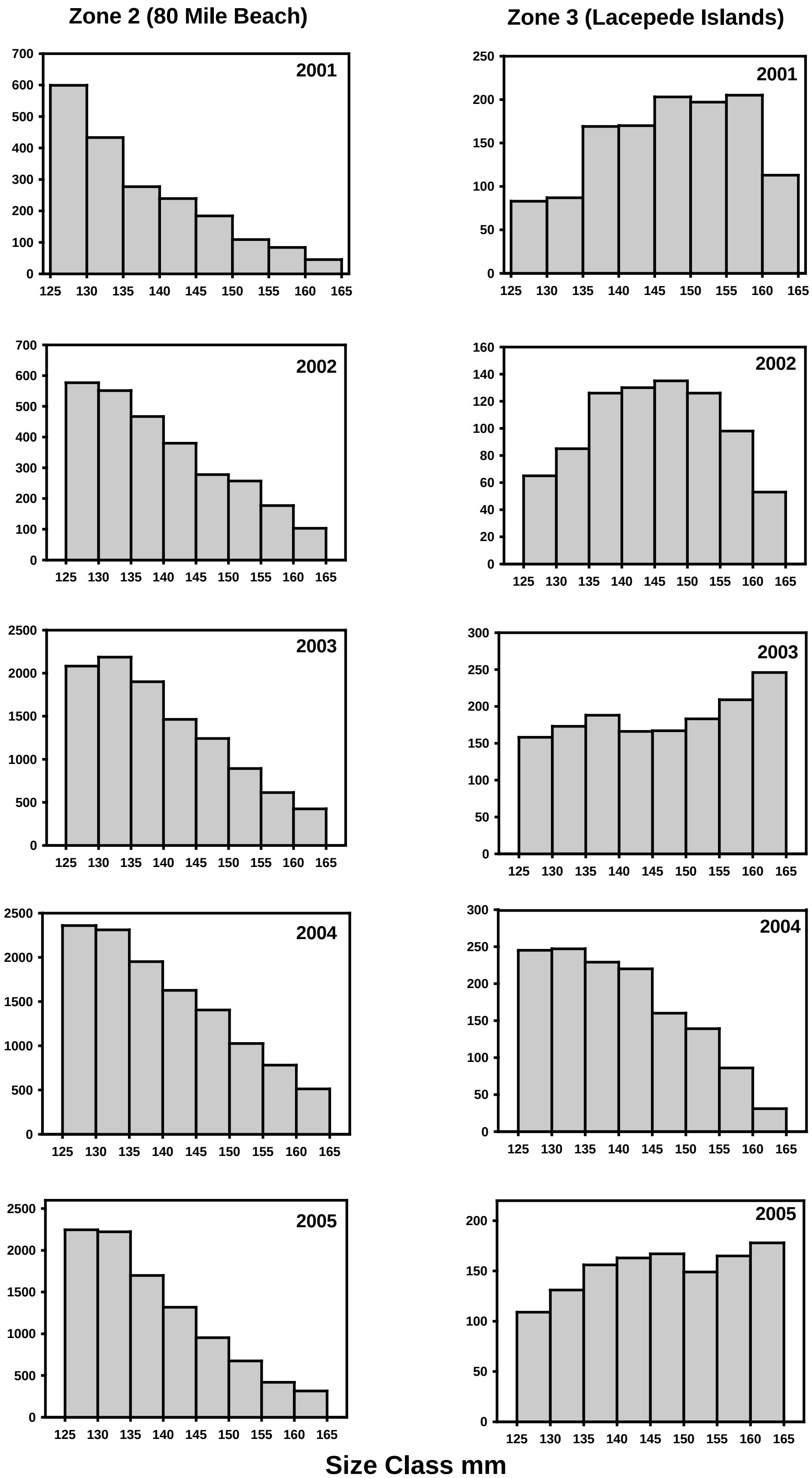


Figure 14. Length frequency distributions of *Pinctada maxima* measured by industry and research personnel in the two main grids of the fishery (4355, and 4454) over the three years (2003-2005) for which comparative data was available. Data is stock distribution prior to discarding. Figure 16 shows the proportional distribution between shell kept and shell discarded.



Zone 2 (80 Mile Beach)
Zone 3 (Lacepede Islands)
2001
2002
2003
2004
2005
125 130 135 140 145 150 155 160 165
Size Class mm

Figure 15. Length frequency distributions of *Pinctada maxima* in Zone 2 and Zone 3 over the five years (2001-2005) for which comparative data was available.

4.4.3 Discard rates by length frequency and area

The overall discard rate (% of shell caught that are released back onto the patch) in 2005 was 39%, although this varied between spatial locations (31-49%; Table 17).

Table 17, Discard rates (% of shell caught released back onto the pearl patch) by area (grid number).

Zone	Grid	Principal Patch	2003 % discard	2004 % discard	2005 % discard
2	4253	Compass Rose	47	34	
	4255	Outside Sand Point	28	31	49
	4354	20 Mile	30	36	37
			42		
	4355	5-10 Mile	42	37	42
			46	25	31
			54		
	4453			28	
	4454	14-21 Mile	30	42	44
			42	39	37
	4455	10-14 Mile	38		
	4553	38 Mile	40	50	35
	4554			37	
	4651	48 Mile/	43		39
	4652	Mandora	38		
3	3060	Lacepedes	32	24	43
					34
	3658	Ganthueme		45	
TOTAL			**39**	**36**	**39**

On average, 63% of the shell returned were either undersize or over size (165 mm+), and 37% were shell of a size normally kept, but considered unsuitable for culture purposes (Figure 16). Discard rate increased with increasing size (Figure 16).

The practice of discarding in the pearl oyster fishery is a function of the selection of animals of smaller sizes and sufficient quality for pearl culture purposes and does not result in significant mortality. Experiments have calculated that mortality from simulated discarding varies between 0 and 2% per annum (Hart & Friedman, 2004).

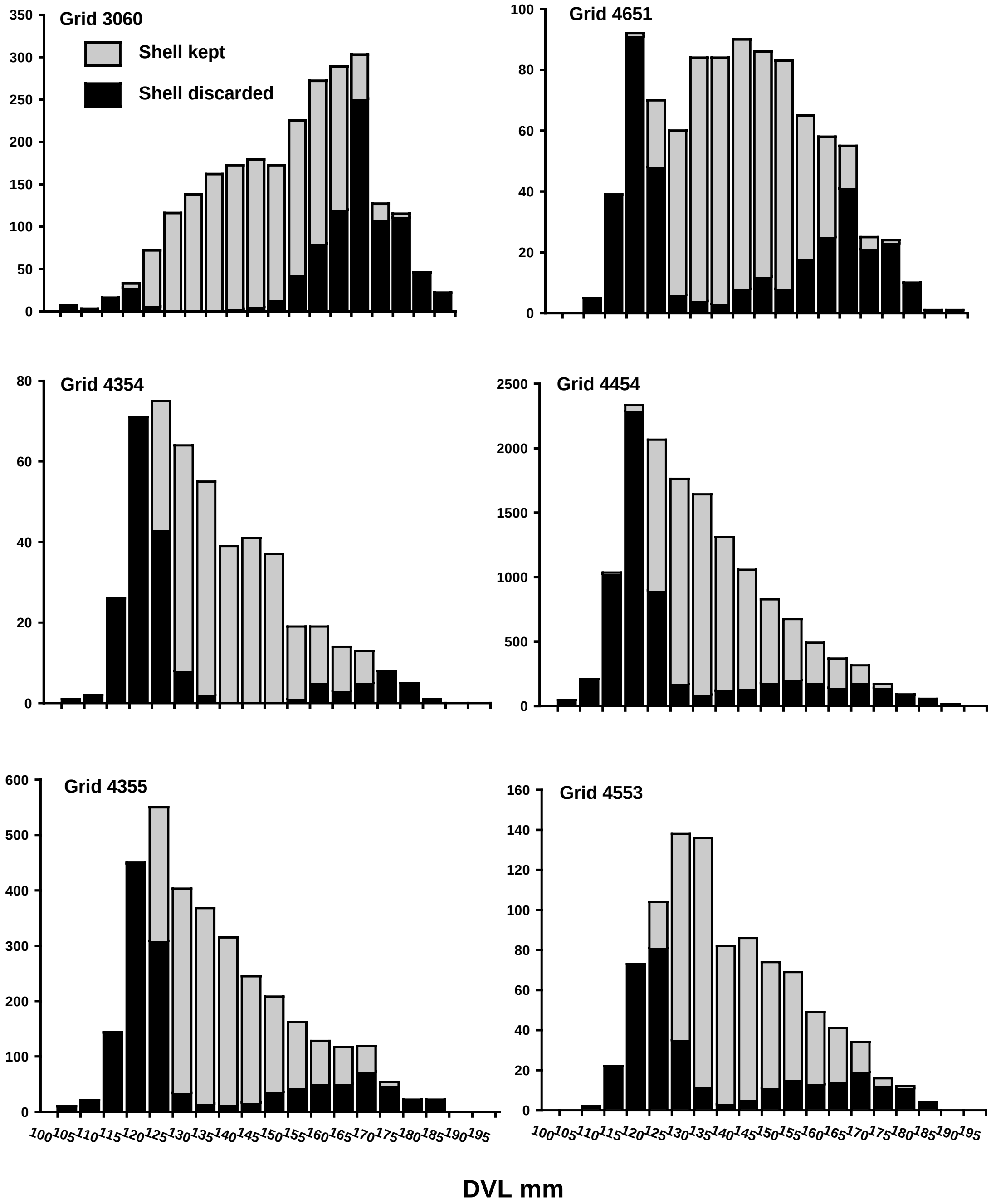


Figure 16. Discard rate (% of oysters caught that are released) of *Pinctada maxima* as a function of shell length (DVM) in different spatial areas of the fishery. Data are from 2005.

4.5 Preliminary predictions of *P. maxima* CPUE using spat abundance data.

Preliminary CPUE predictions for Zone 2 and Zone 3 were established for 2006-2008 (Table 18), principally to highlight the concept rather than provide robust and accurate estimation. As explained in Section 3.6, 2005 was the only year that had sufficient recruitment information due to lag-times, hence the equation derived could not be statistically fitted to the data. However, to illustrate the methodology, the 2005 correlations were assumed to apply for future CPUE. At minimum, another 5 - 7 years of temporal correlations of spat abundance with commercial fishery CPUE is required before the robustness of these predictions can be reliably determined.

In Zone 2, stock abundance and hence catch rates are predicted to remain stable in 2006, and then increase over the next 3-5 years (Table 18). In Zone 3, CPUE will increase in 2006 from 2005, and then decrease the following two years (Table 18).

Table 18. Predicted pearl diver catch per unit effort (CPUE) of *Pinctada maxima* in Zone 2 (80 Mile Beach) based on data from the piggyback spat recruitment index (1+ age class) lagged at *n*-3 and *n*-4 years, where *n* is the fishing year of interest

Year (*n*)	**1+ Spat predictive index* mean [(*n*-3) + (*n*-4)]**	**CPUE (Shells caught per diver hour**	**Predicted CPUE (Shells caught per diver hour**
			Zone 2
2005	5.68	33.6	
2006	5.94		35
2007	6.9		41
2008	6.2		37
2009			?>50
			Zone 3
2005	10.02	26.3	
2006	13.18		34.6
2007	8.13		21.3
2008	3.1		< 20

* number of spat per 1000 shell checked

4.6 Factors affecting catch rates

4.6.1 The effect of GPS and Southern Oscillation Index (SOI)

In both Zone 2 (Table 19) and Zone 3 (Table 20), GPS was a highly significant factor affecting the temporal variability in CPUE. In Zone 2 it explained around 66-70% of the total variation in yearly catch rates (Table 19). In Zone 3 it explained around 45-50% of yearly variation in catch rates (Table 20). The SOI index had a significant effect on CPUE during the year of fishing in Zone 2, but was not a contributing factor at any lagged years (Table 19). In La Niña years when SOI is high, CPUE is also high. In El Niño years when SOI is low, CPUE is also low (Figure 17). However, in Zone 3, SOI was not a contributing factor to variability in CPUE, either during the year of fishing, or at any prior years (Table 20).

This analysis demonstrates the importance of changes in technology to variability in CPUE, and the importance of environmental conditions as measured by the SOI, on the catchability of pearl oysters. For example, water visibility, which is hypothsised to me a major contributor to CPUE, may be higher during La Niña years. Data collection has begun on this factor, however it will be some time before a reasonable time series trend is available for comparison.

However, it also appears that SOI is not an adequate index of environmental conditions that influence recruitment. Further work is required to understand the key environmental variables that trigger the recruitment pulses witnessed in 2005.

Table 19. The significance of each parameter of the considered factors (one SOI covariate and the GPS factor) in a two-factor regression model modelling the yearly CPUE for Zone 2 (*n* = 27). The R^2 for each of these models is also presented. The significance of each SOI on CPUE was tested in separate models due to the correlation of these indices.

SOI Lag	Parameter (*P*-value)		R^2
	SOI	GPS	
0 lag	0.35 (0.03)	7.36 (< 0.01)	0.72
2 lag	-0.26 (0.12)	7.65 (< 0.01)	0.69
3 lag	-0.09 (0.61)	7.57 (< 0.01)	0.66
4 lag	0.15 (0.33)	7.73 (< 0.01)	0.67
5 lag	-0.04 (0.80)	7.59 (< 0.01)	0.66

Table 20. The significance of each of the considered factors (one SOI covariate and the GPS factor) in a two-factor regression model modelling the yearly CPUE for Zone 3 (*n* = 26). The R^2 for each of these models is also presented. The significance of each SOI on CPUE was tested in separate models due to the correlation of these indices.

SOI Lag	Parameter (*P*-value)		R^2
	SOI	GPS	
0 lag	0.03 (0.89)	6.96 (< 0.01)	0.45
2 lag	-0.42 (0.08)	6.95 (< 0.01)	0.52
3 lag	0.05 (0.82)	7.00 (< 0.01)	0.45
4 lag	0.15 (0.54)	7.02 (< 0.01)	0.46
5 lag	-0.07 (0.74)	6.97 (< 0.01)	0.45

The net outcome of this analysis is that management decision analyses (e.g. TAC determination) will use the historical data after the introduction of GPS (1994 – present), in conjunction with the predictive piggyback spat index. An examination of patterns in catch rates during that time shows an increased average and increased variability, post 1993, that is clearly explained by fishing efficiency increases as a result of GPS technology (Figure 17).

An equally valid hypothesis however, which is difficult to examine experimentally, is that abundance increases coincided with the introduction of GPS, and therefore have been incorporated into the GPS effect. Increased abundance can be attributed to the cessation of MOP fishing in the early 1980s, and the continual build-up of brood stock over time until recruitment has been enhanced. Some evidence is available by comparisons with from 0+ settlement data on the 80 Mile Beach collected in the early 1990s by Joll (1996).

A statistical comparison between 1991-1995 and 2001–2005 settlement (0+ class) was not significant (d.f. =8; t = -1.84; p = 0.11), however mean 0+ settlement rose by 100% from 4.8 spat (per 1000 shell) to 10.3 spat (per 1000 shell). This result was largely influenced by the record 2005 settlement, however it does imply that settlement has increased overall. Future sampling will enable more comprehensive examination of this hypothesis.

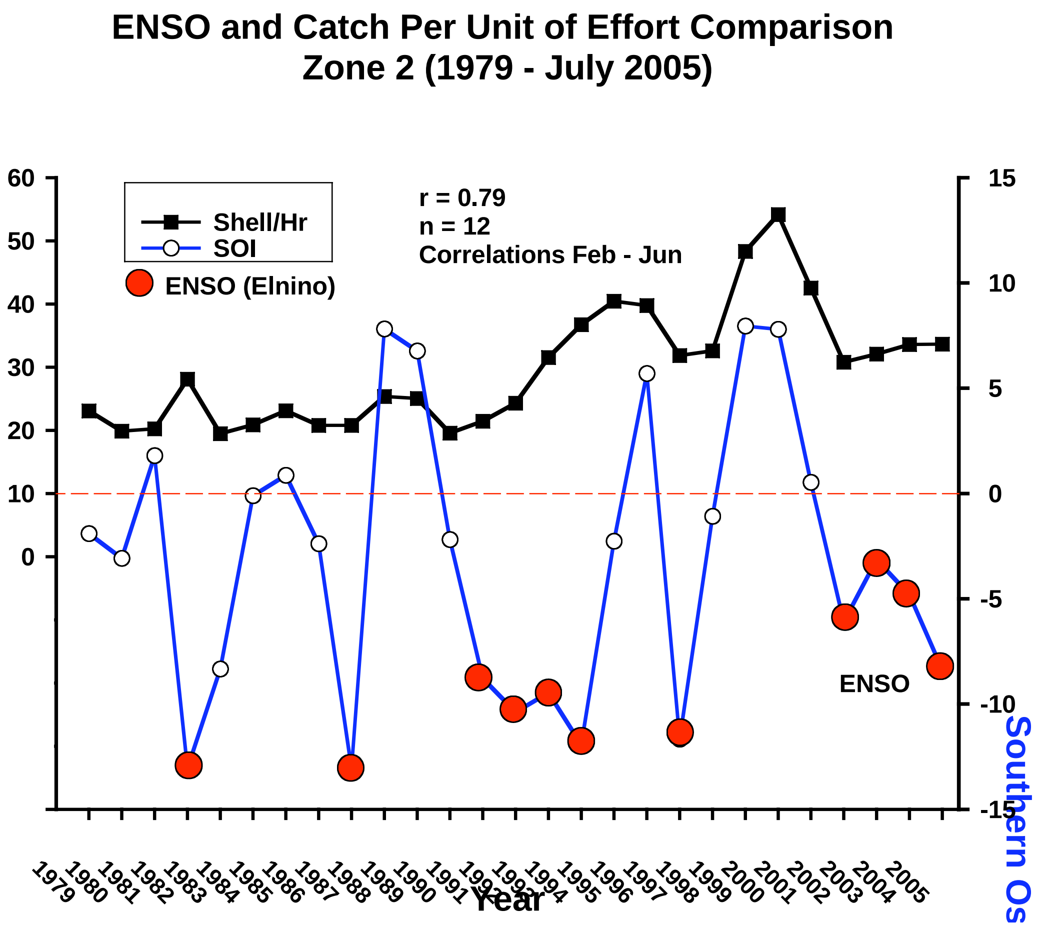


Figure 17. Relationship between CPUE (shells/hour) in Zone 2 and the Southern Oscillation Index (SOI), which is a measure of the strength of El Niño, in the same year.

4.7 Transport and recruitment of pearl oyster larvae on the 80 Mile Beach (Scott Condie and Anthony Hart)

4.7.1 Modeled currents and sea-levels

Instantaneous current patterns on the NWS were dominated by strong tides, with speeds approaching 2 m s^{-1} during the spring-tide (Figure 19a). In the main fishing areas around Eighty Mile Beach, the tidal movements were predominantly in the cross-shore direction and diminished with distance offshore. The model currents have been shown to compare favorably with observations around the Dampier region to the west (Condie et al. 2005a). However, no direct current observations have been taken in the Eighty Mile Beach region (Godfrey and Mansbridge 2000). The best indication of model performance in the local region was therefore provided through comparisons of sea-level variability.

Sea-level was strongly dominated by the very large tidal signal, with ranges up to 10 m in King Sound. The model generally reproduced the tidal sea-level signal quite accurately, with correlation coefficients increasing from r = 0.87 at Broome to r = 0.96 at Port Hedland (Condie et al. 2005a). However, it is the lower frequency component that largely controls net transport over the pelagic larval phase (24 to 31 days). Since sub-tidal currents are generally highly correlated with sub-tidal sea-level differences, model performance in the Eighty Mile Beach region was examined in terms of sea-level differences between Broome and Port Hedland. This analysis revealed a strong coastally trapped wave signal in both the model and observations, with a period of approximately 14 days in both instances. However, it is the variability over the typical larval phase that is of most immediate interest. For example, comparisons of the running mean of the sea-level difference over 28 days produced a correlation of r = 0.89 (Figure 18b).

Monthly-averaged surface currents during the period October to December (main spawning period) were typically northeastward at a few centimeters per second (Figure 19b). However, close to Eighty Mile Beach the surface flow was directed offshore, suggesting a net upwelling over the monthly timescale. These currents patterns were a response to the prevailing westerly winds and are consistent with the few satellite-tracked ocean-drifters observed in the area at this time of the year (Cresswell et al. 1993). The depth averaged currents were weaker and tended to form a clockwise gyre off Eighty Mile Beach (Figure 19c). The resulting flow close to the coast was predominantly westward, counter to the prevailing winds. This monthly averaged pattern persisted throughout the spawning period (Figure 19d).

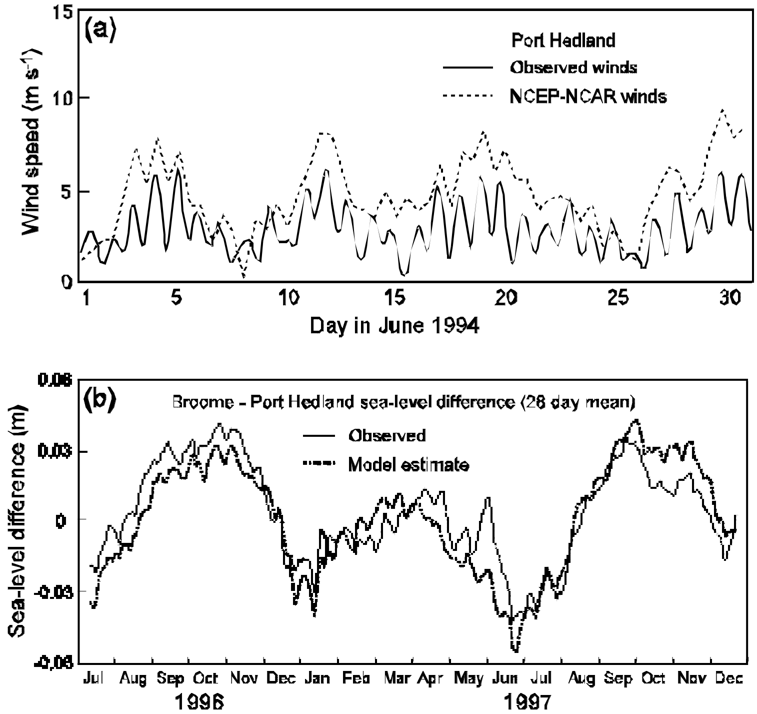


Figure 18. (a) Comparison between local observed winds at Port Hedland and the NCEP-NCAR winds used to force the model for June 1994. (b) Comparisons of observed and modeled low-frequency sea-level difference between Broome and Port Hedland based on a 28 day running mean.

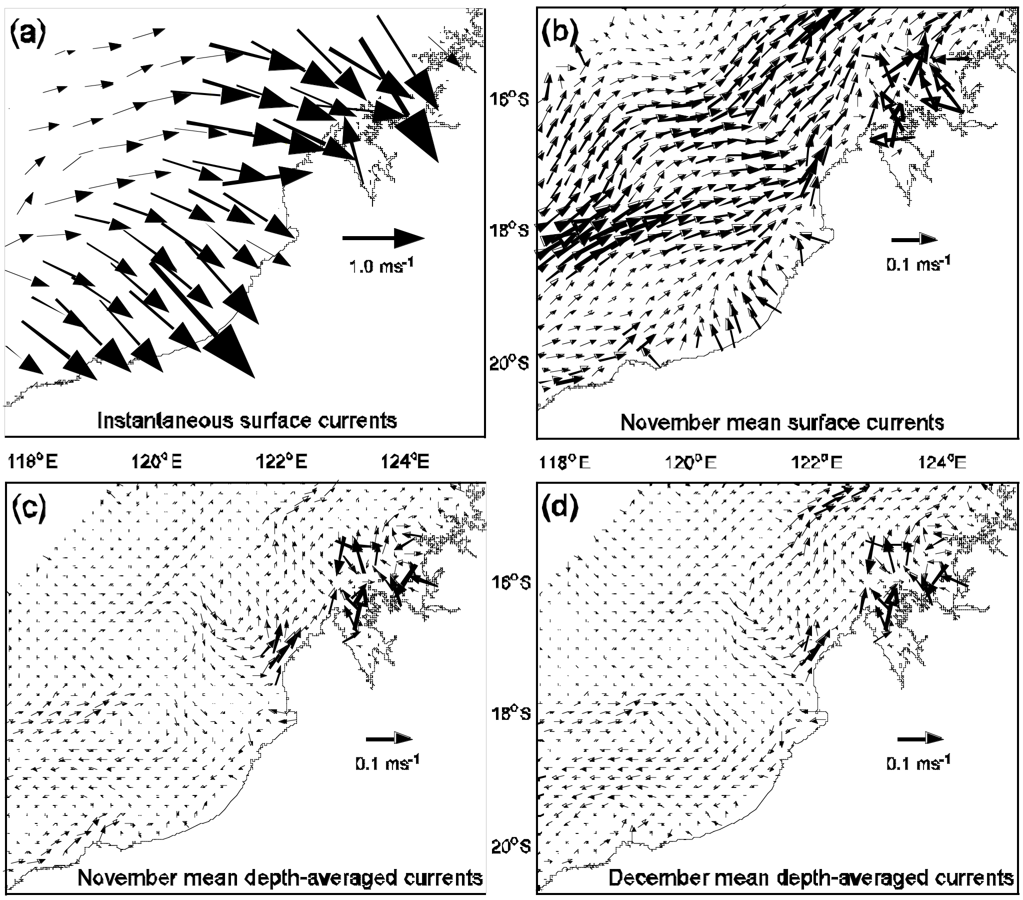


Figure 19. (a) Example of flood-tide currents under spring-tide conditions. (b) Monthly mean surface currents (depth = 1.5 m) for November based on six years of model runs (1994-99). (c) Monthly mean depth-averaged currents for November based on six years of model runs (1994-99). (d) As in (c) for December..

4.7.2 Estimates of settlement distribution

The surveyed broodstock (MOP) distribution (Figure 20a) showed low to moderate relative abundances (0 to 60 shell hr^{-1}) around the 10 m depth contour, with a tendency towards higher values at the northern extremity of the sampling area (60 to 120 hr^{-1}). However, the largest abundances (110 to 160 hr^{-1}) were found in a patch further offshore around the 30 m depth contour. Potential larval settlement distributions were estimated by assuming that MOP survey abundances were proportional to the spawning population (although results were qualitatively very similar when all cells with surveyed MOP were given equal weighting).

Results averaged across the model runs (1994 to 1999) indicated two main potential settlement areas (Figure 20b). The larger was centered just inshore of the 10 m depth contour (121°24’E, 19°6’S), with the smaller centered just inshore of the 20 m depth contour (121°7’E, 19°11’S). Since larvae could potentially settle at any time during the tidal cycle, the size of these areas was largely determined by the dimensions of the tidal ellipse. The relative settlement rate in the two areas varied from year to year and in 1994 the model results showed more settlement offshore than onshore (not shown). However, the predicted settlement areas were not associated with the two distinct spawning areas. Rather, most MOP regions contributed to both settlement areas (C to F in Figure 20a and 21a) reflecting temporal and spatial variability in flow patterns within the 2.5 month spawning period. The main exception to these trends was the surveyed area near the 30 m depth contour, whose modeled larvae tended to move into deeper water (≥ 40 m) to the southwest without contributing to either of the main settlement areas (A in Figure 20a and 22a).

The model predicted settlement region covers nearly all the areas surveyed for spat, with predicted high settling rates corresponding with the main survey area (cf. Figure 20b and Figure 20c). However, spat surveyed further offshore and to the north (Figure 20c) corresponded to low settlement rates and may have originated from MOP outside the MOP survey area. There were also large areas of predicted settlement, both near-shore and offshore, that were not in the area of the spat surveys. While spat may have existed in some of these areas, the limited availability of suitable habitat would likely have resulted in low abundances.

4.7.3 Estimates of spawning distribution

The surveyed spat distribution tended to follow the 10 m depth contour along Eighty Mile Beach at low to medium relative abundances (0 to 20 per thousand shells) with a bias towards deeper water to the north (Figure 20c). There were a few high abundance cells (20 to 30 per thousand shells) in this zone, with more in habitats further offshore around the 15 m and 30 m depth contours (Figure 20c). Potential spawning distributions were estimated by assuming that the spat survey abundances were proportional to the settling population (although results were qualitatively very similar when all cells with surveyed spat were given equal weighting).

Estimated spawning areas associated with the surveyed spat distributions were centered just inshore of the 10 m depth contour (121°24’E, 19°6’S), but relatively high values extended offshore almost to the 20 m depth contour and onshore almost to the coast (Figure 20d). The size of these areas was again a function of the tidal ellipse and there was very limited interannual variability (not shown). Spat counted in the main survey area along the 10 m depth contour were mainly spawned in this area (C, D and E in Figure 20c and Figure 21b), although cell E also received model larvae from further to the northeast. The model indicated that spat surveyed further south (B) and north (F) would have come from spawning in deeper water, while those offshore around the 30 m depth contour (A) would have come from marginally shallower depths to the northeast (Figure 20c and Figure 21b).

Apart from extending into very shallow water, the spawning area estimated from the surveyed spat (Figure 20d) was consistent with the surveyed MOP distribution (Figure 20a). The main exception was the offshore MOP (A in Figure 20a), which the model suggests spawn into deeper water outside of the spat survey region (Figure 20a).

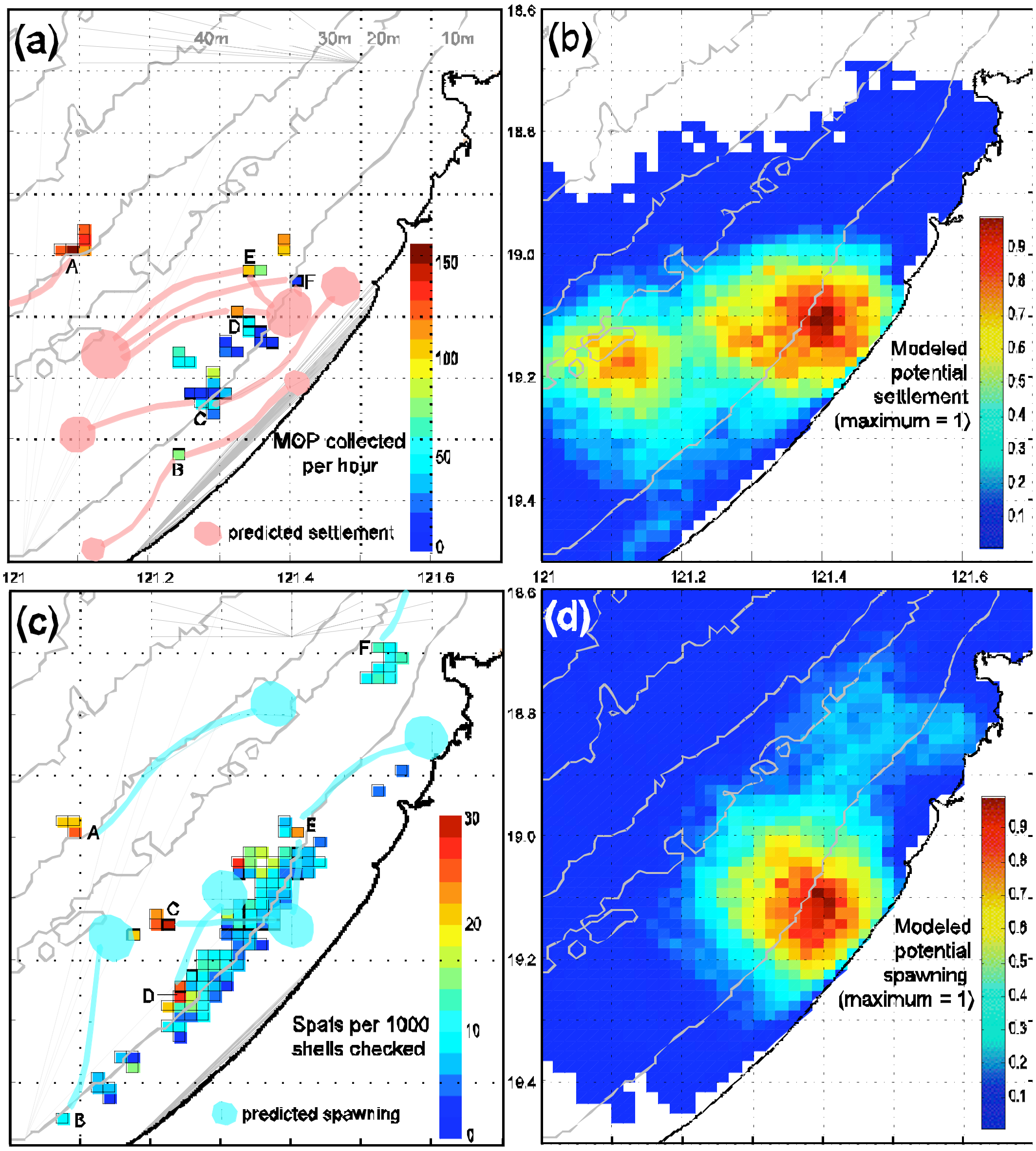


Figure 20. (a) Relative abundance of broodstock (MOP) off Eighty Mile Beach expressed in terms of the number collected per hour of vessel drift during the survey (Hart and Friedman 2004) overlain by a schematic summary of modeled downstream settlement areas from selected cells A to F (corresponding quantitative predictions for A to F are shown in Figure 19a). (b) Estimated settlement distribution (ignoring habitat availability) averaged across all model years (arbitrary units with maximum = 1). (c) Relative abundance of spat off Eighty Mile Beach expressed in terms of average number of spat found per 1000 shells checked, overlain by a schematic summary of modeled upstream spawning areas from selected cells A to F (corresponding quantitative predictions for A to F are shown in Figure 5b). (d) Estimated spawning distribution averaged across all model years (arbitrary units with maximum = 1).

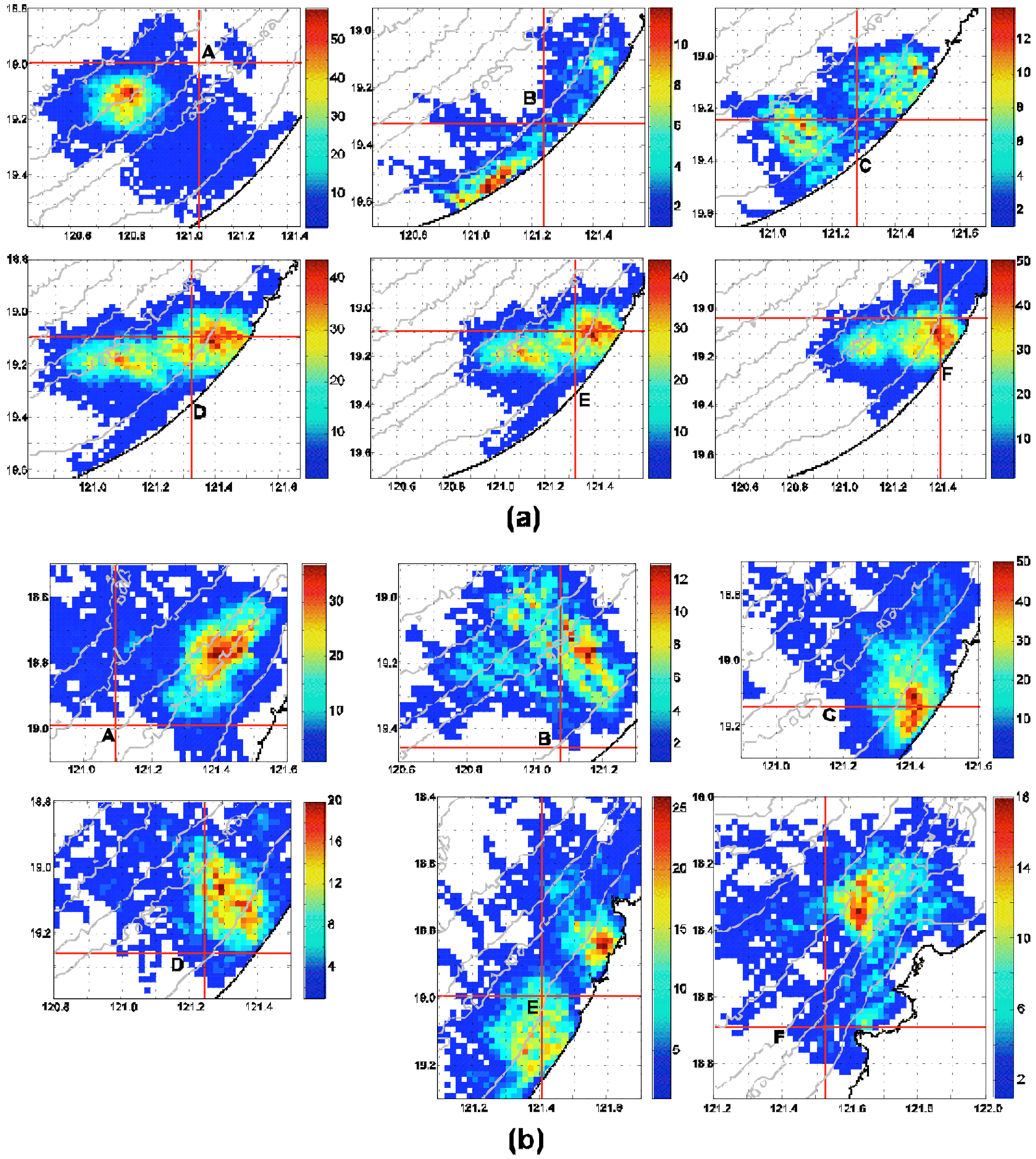


Figure 21. (a) Relative likelihood of settlement following spawning at the cell marked by the cross-hairs. (b) Relative likelihood of spawning contributing to settlement at the cell marked by the cross-hairs. In both (a) and (b) results are averaged across all model years (1994-1999), the color-bars indicate the number of trajectories connecting an given cell with the cell marked by the cross-hairs, and depth contours are at 10 m intervals.

4.8 Preliminary management rule for the *Pinctada maxima* fishery

Quota (TAC) decisions in Zone 2 and Zone 3 of the pearl oyster fishery are currently based on a decision rule formulated in the early 1990s. The existing rule adjusts TAC by 10% increment based on a comparison of last year's catch rates against a biological reference point (BRP), which is the average catch rate from the 1983 – 1992 fishery.

As an outcome from this project, a new forecasting management rule (FMR) using the piggyback spat was developed. The FMR also uses BRPs that reflect the current fishery (1996-2005), in comparison to the old decision rule, which was based on the performance of the fishery in the 1980s and early 1990s, prior to the introduction of GPS. The highly significant effect of GPS on the CPUE index (Table 19) indicates that a new time series of data needs to be utilised, however this time series should reflect the best estimates of the state of the stocks.

The FMR is still in an early developmental phase, and shall be fine-tuned over the coming 3-4 seasons as a greater time-series of recruitment data and understanding of the lags between settlement and recruitment to the fishery become available.

The decision framework for the FMR is as follows.

a) compare the predicted index (PI) and current stock abundance index (CI) with their respective biological reference points,
b) determine if CI and PI fall below or above the trigger points (TPs) of their respective BRPs, and
c) adjust TACs, if necessary, on the basis of that determination.

4.8.1 Predicted index of stock level (PI)

The predicted indices are based on the averaging the piggy-back spat year-class abundances at an appropriate lag that will reflect the expected commercial catch rate of oysters in the year for which the quota is being set. This is developed for the 2 year classes of spat, 0+ and 1+, shown as PI (0+) and PI (1+), respectively:

PI (1+) = average 1+ spat abundance (n - 3; n –4),

PI (0+) = average 1+ spat abundance (n - 4; n – 5),

where n is the year for which TAC is being set. These equations assume that the commercial catch rates are primarily based on 2 year-classes.

4.8.2 Current index of stock level (CI)

CI = CPUE (*n* - 1), where *n* is the year for which TAC is being set. The CPUE is an index of the abundance of the three principal age classes (4-6 years old) assumed to make up the majority of the commercial catch.

4.8.3 Biological Reference Points (BRPs)

4.8.3.1 BRPs for the predictive stock index (0+/1+ spat)

The preliminary BRPs based on the PI's are calculated using data from the current project, and earlier piggyback spat sampling reported by Joll (1996).

BRP (1+) = average 1+ spat PI ($n = 7$) = 5.71 spat per 1000 shell.

BRP (0+) = average 0+ spat PI ($n = 7$) = 6.44 spat per 1000 shell.

Note that the calculation of the BRP for the 0+ age class did not include the record spat collection in 2005 (33 spat per 1000 shell; see Figure 7) because this is currently perceived as an anomaly. This decision may be reviewed in the future.

4.8.3.2 BRP for the current stock index (diver CPUE)

BRP (CI) = average Zone 2/3 CPUE (1996-2004) = 38 shells per hour.

Note that the calculation of the BRP for the current stock index (CI) is based on the raw CPUE data from the years in which GPS has been introduced to the fishery, as GPS was shown to be the major influence on CPUE since 1979. In the future, the decision to use raw CPUE may be reviewed in favour of log-transformed CPUE indices. The back-transformed log-mean of CPUE is 37 shells per hour.

4.8.4 Trigger Points (TP)

The biological reference points (BRPs) for predicted indices of stock level and the current index have been standardized in order to examine the percent variation of the annual indices from the BRPs. The trigger points, that if breached will result in a recommended quota change, are currently proposed as ± 25% of the BRPs for the predicted index and current index (Figure 22 and Figure 23). However, given the large variability in spat settlement compared to the commercial catch rate, it is possible that the trigger point for the predictive index may need to be greater than ±25%, say ± 50%, of the BRP. This will become clear with future years data on settlement trends.

4.8.5 Quota Adjustments

Quota adjustments can proceed in ± 10% increments from the current baseline level of quota (457,000 shell) according to the preliminary TAC decision table (Table 21). Otherwise they are to remain at the baseline level.

Table 21. Total Allowable Catch (TAC) Decision Table in relation to predicted and current stock indicators, trigger points, and reference points. A graphical representation of this is seen in Figure 22 and Figure 23. Predicted stock levels obtained from 1+ spat data

		Current stock levels (in relation to BRP)		
		>25%	Between ± 25%	<25%
Predicted stock levels (in relation to BRP)	>25%	INCREASE	INCREASE	NO CHANGE
	Between ± 25%	INCREASE	NO CHANGE	DECREASE
	<25%	NO CHANGE	DECREASE	DECREASE

4.8.6 Assumptions of the management rule

There are two key assumptions that need to be verified in the future. These are:

1. The legal-sized catch is made up principally of 4 – 6 year old oysters, although the faster growing 3 year old oysters may also be contributing.
2. The relative weighting of the 3 year classes is assumed to be dominated by 4-5 year olds, but it is expected that the youngest year class will be dominating the catch based on length frequency data.

4.9 TAC Decision for 2006 (Zone 2 only)

4.9.1 1+ spat predictive index

At this point, the 1+ spat is considered the predictive index, with the 0+ spat providing preliminary information on upcoming stock abundances. The 1+ spat will provide a 3-year forecasting ability from 2006 to 2008.

For the 2006 season, both predictive and current stock indices are within the boundaries of the trigger points (Figure 22). Therefore no change to the baseline level TAC was recommended and TAC to remain at 457,000 oysters. In 2007, the predicted stock level is near the upper trigger point for a quota increase (Figure 22), and when considered against the predicted level from the 0+ spat index (Figure 23), a quota increase is very likely.

At the time of report completion, the TAC for 2006 was in fact set at a higher level than the preliminary FMR recommended (502,500 oysters). The general consensus of

PIAC was that the trigger points and reference points were too conservative and did not properly account for the hypothesis of increased abundance coinciding with GPS technology introduction, and therefore were being masked by this effect. Further testing of this hypothesis will occur alongside discussion and development of the management rule during 2006 and 2007.

4.9.2 0+ spat preliminary index

The 0+ spat predictive index provides a 4-year forecasting ability which extends to 2009, and shows general agreement with the 1+ indicator for the 2006 fishing year (Figure 23). For example, in 2007 the predicted stock level exceeds the trigger point for a quota increase, which concurs with the prediction from the 1+ index (Figure 22). Note that the record 0+ spat settlement of 2005 has resulted in a very high predicted stock level in 2009 (260% above the reference point; Figure 23). This will need to be confirmed with the assessment of the 1+ spat index in 2006.

4.10 General Discussion

This study has resulted in significant advancement in our knowledge of the temporal and spatial dynamics of the *Pinctada maxima* stocks in Western Australia. The similarity of patterns in settlement between the silver-lipped pearl oyster, and its smaller, unexploited relative, *Pinctada albina*, points to environmental and oceanographic processes as key drivers of the system. However, the detection of spatial differences in settlement also suggests the importance of localised processes such as small circulation eddies, in determining ultimate settlement patterns. For example, the record settlement detected in 2005 did not occur in areas north and south of the main pearl reefs. In time, the accumulation of settlement data, commercial stock abundance data (CPUE), and environmental and oceanographic data, will enable closer understanding of the whole system. In the meantime, the project has generated enough information for a new management system for the pearl oyster fishery to be considered. The details and operation of this management system will developed and refined through the Pearling Industry Advisory Committee (PIAC).

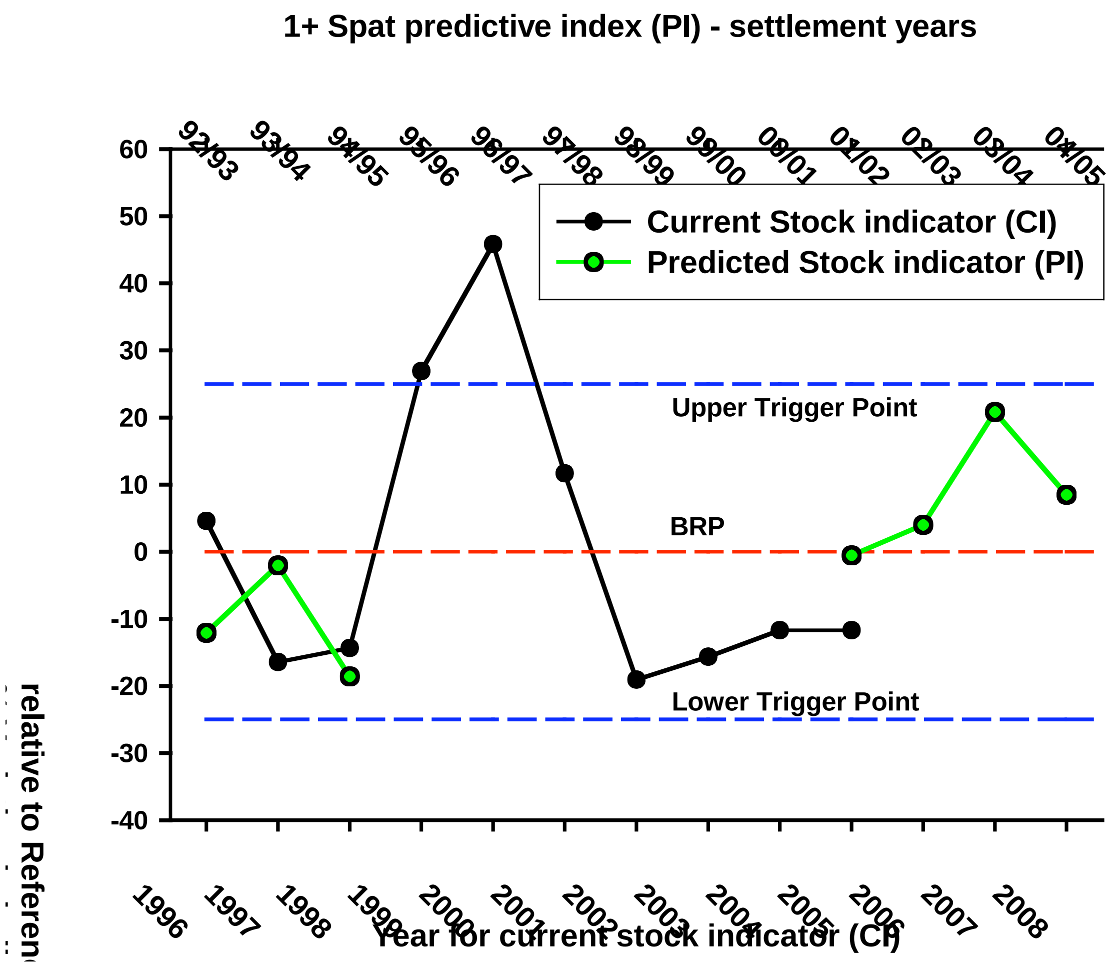


Figure 22. Performance Measure for Zone 2 TAC decisions using 1+ spat predictions. Percentage variation in the 1+ spat predicted (PI) and current stock indicators (CI) in relation to the biological reference points (BRP) and trigger points.

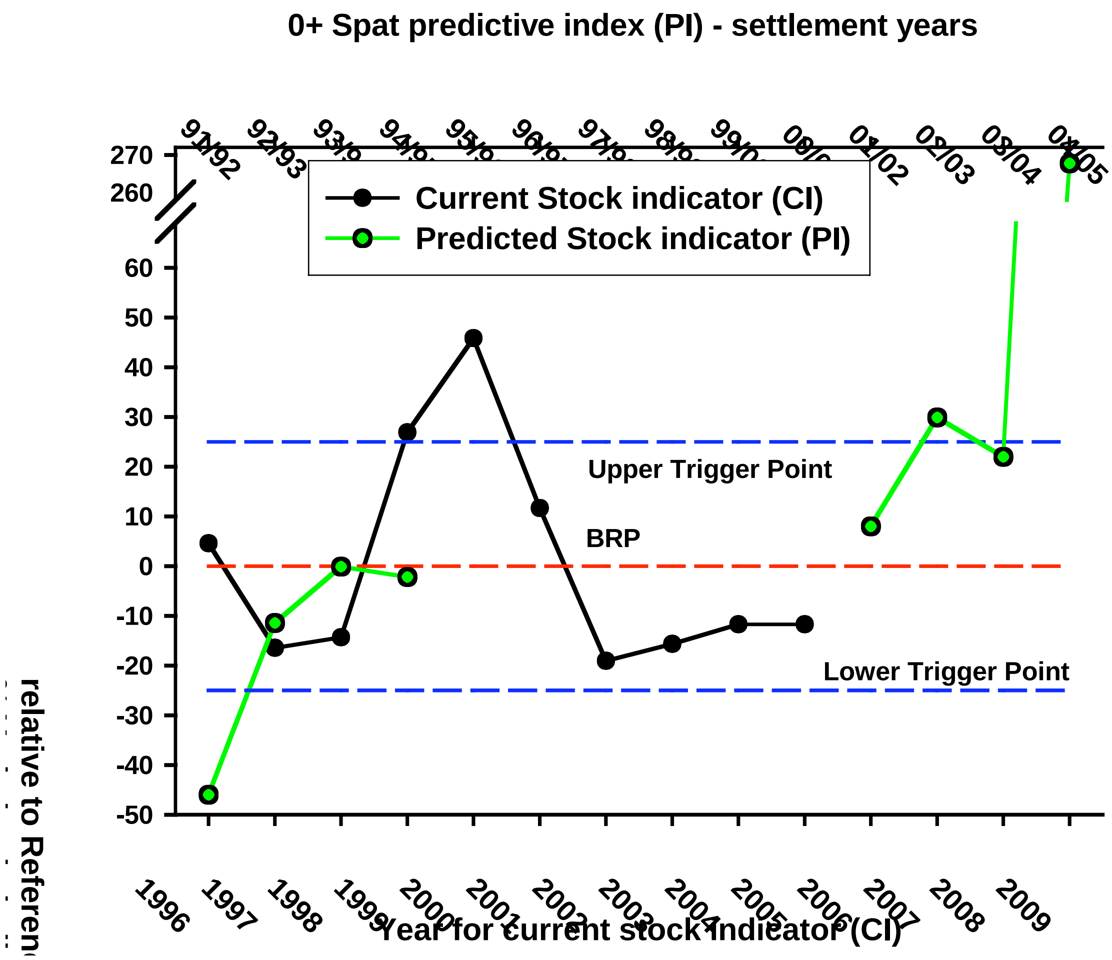


Figure 23. Performance Measure for Zone 2 TAC decisions using 0+ spat predictions. Percentage variation in the 0+ spat predicted (PI) and current stock indicators (CI) in relation to the reference levels and trigger points.

5 Benefits

The most immediate beneficiary of the results of this study is the Pearling Industry of Western Australia, who now have a forecasting management tool in which they can predict stock availability up to 4-6 years ahead. This will enable them to plan more effectively their marketing strategies, as well as integrate their pearl oyster breeding and grow-out more effectively with the wild-catching sector. Secondly, the West Australian public benefits because of the enhanced management ability of the oyster stocks, thus reducing risk of stock depletion.

6 Further Development

This project has identified the spatio-temporal dynamics of *Pinctada maxima* and *P. albina* recruitment in the pearl oyster stocks of Western Australia, and evaluated some of the principal environmental drivers of this recruitment. Work is needed however, on the temporal variability in oceanographic circulation within the *Pinctada maxima* stocks, and the mapping of this to temporal variability in spat settlement. The way to achieve this is to focus the modelling of larval dynamics to the specific reefs/habitats identified in this study over the specific years for which data is available. The other major hypothesis that needs further investigation is whether the co-incidence of GPS introduction and abundance increases have led to the masking of the latter effect by the former. More data on settlement rates, and comparison with early studies in the 1990s will enable this to be considered.

7 Planned Outcomes

The main project outputs were described in the performance indicators. Each of these will be addressed.

1. Development of a comprehensive database of piggyback spat data – gain a spatial and temporal knowledge of the relative abundance of pre-recruits to the pearl fishery

A comprehensive database was developed, and the project gained sufficient spatial and temporal knowledge of pre-recruit abundance to enable it to be used in the TAC decision-making process.

2. Presentation of piggyback, length frequency and environmental information to annual pearl oyster management meetings, starting September/October 2000.

Presentation of the data has been made at every annual meeting since 2000, and will continue be made into the future, as PIAC (Pearling Industry Advisory Committee) endorsed the continuation of the piggyback spat program, as a primary tool for management.

3. To further determine important environmental factors affecting recruitment – gain a more holistic understanding of the pearl oyster fishery.

The project determined that the Southern Oscillation Index was more important to the catchability of pearl oysters, than to recruitment, and that the centre of pearl oyster spawning and settlement determined by modelling of oceanographic currents were the main fishing areas of the fishery.

All these project outputs contributed towards achievement of the final planned outcome, which was to bring a new paradigm to the management of pearl oyster stocks. A new TAC decision rule, which incorporated the piggyback spat recruitment index was developed and applied to TAC management for the 2006 fishery. The rule is still in its developmental stage, however, the eventual goal is that it will be able to align fishing effort more closely with stock abundance.

8 Conclusion

The project achieved its goal of developing a formal sampling regime to estimate recruitment and age-class abundance within the commercially fished pearl oyster stocks, with a view to obtaining a predictive stock index. There was good agreement amongst industry and research datasets as to the nature of the temporal trends, particularly in the 0+ age class, and reasonable agreement with respect to length-frequency trends. Thus, there is significant potential for industry data to provide the recruitment index, and length-frequency data, provided the protocols of sampling are adhered to. The data was also used to examine spatio-temporal trends and assist in modelling of larval transport and connectivity between populations. A major conclusion was that the most significant effect on commercial fishery catch rates in the last 25 years was the introduction of GPS technology onto the pearling vessels. The project has resulted in a significant advance in our biological knowledge, and consequently, management capacity to ensure the future sustainability of the *Pinctada maxima* stocks in Western Australia

9 References

Beer AC (1995). Spat collection and growth of juvenile pearl oysters (Family Pteriidae) at Pioneer Bay, Orpheus Island. Honours Thesis. James Cook University of North Queensland. 88p.

Bruce, B. D., S. A. Condie, & C. A. Sutton. 2001. Larval distribution of blue grenadier (Macruronus novaezelandiae Hector) in south-eastern Australia: further evidence for a second spawning area. Mar. Freshwat. Res. 52: 603-610.

Caputi, N., Brown, R.S., Phillips, B.F. 1995. Predicting catches of the western rock lobster (*Panulirus cygnus*) based on indices of puerulus and juvenile abundance. ICES mar. Sci. Symp., 1999: 287-293.

Condie, S.A., Mansbridge, J.C., Hart, A.M., Andrewartha, J.M. (2006). Transport and recruitment of silver-lip pearl oyster larvae on Australia's North West Shelf. *Journal of Shellfish Research.* 25 (1): 179 – 185.

Condie, S. A., J. Andrewartha, J. V. Mansbridge & J. Waring. 2005a. Modelling Circulation and connectivity on Australia's North West Shelf: North West Shelf Joint Environmental Management Study Technical Report, CSIRO Marine Research, 61 pp

Condie, S. A., J. Waring, J. V. Mansbridge & M. L. Cahill 2005b: Marine Connectivity patterns around the Australian continent. Environ. Mod.. Software 20: 1149-1157.

Condie, S. A., N. R. Loneragan & D. J. Die. 1999. Modelling the recruitment of tiger prawns (Penaeus esculentus and P. semisulcatus) to nursery grounds in the Gulf of Carpentaria, northern Australia: implications for assessing stock-recruitment relationships. Mar. Ecol. Prog. Ser. 178: 55-68.

Cresswell, G., A. Frische, J. Peterson & D. Quadfasel. 1993. Circulation in the Timor Sea. J. Geophys. Res. 98: 14379-14389.

Eanes, R. & S. Bettadpur. 1995. The CSR 3.0 global ocean tide model. Center for Space Research, Technical Memorandum, CST-TM-95-06.

Godfrey, J. S. & J. V. Mansbridge. 2000. Ekman transports, tidal mixing, and the control of temperature structure in Australia's northwest waters. J. Geophys. Res. 105: 24021-24044.

Hart AM, Joll L (2006). Growth, mortality, recruitment, and sex ratio in wild stocks of the silver-lipped pearl oyster Pinctada maxima (Jameson)(Mollusca: Pteriidae) in Western Australia. *J. Shellfish Research.* 25(1): 201 - 210.

Hart A, Skepper C, Joll L (1999). 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 fishery. Final report to Fisheries Research and Development Corporation. FRDC project No. 95/41.

Hart AM, Friedman KJ (Editors) 2004, *Mother-of-pearl shell* (Pinctada maxima): *Stock evaluation for management and future harvesting in Western Australia*, FRDC Project 1998/153, Fisheries Research Contract Report No. 10, Department of Fisheries, Western Australia, 84p.

Herzfeld, M., J. Waring, J. Parslow, N. Margvelashvili, P. Sakov & J. Andrewartha. 2002. MECO, Model of Estuarine and Coastal Oceans, V4.0, Scientific Manual, CSIRO Marine Research.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K.C. Mo, C. Ropelewski, J. Wang, A. Leetmaa, R. Reynolds, R. Jenne & D. Joseph. 1996. The NCEP/NCAR 40-year reanalysis project. Bull. Amer. Meteor. Soc. 77: 437-471.

Joll L (1996) Stock Evaluation and Recruitment Measurements in the W.A. Pearl Oyster Fishery. Fisheries Research And Development Corporation; Western Australia Fisheries Department, Perth; Canberra Fisheries Research and Development Corporation, ((FRDC project; 92/147)); 63p.

Pass DA, Dybdahl R, Mannion MM (1987). Investigations into the causes of mortality of the pearl oyster, *Pinctada maxima* (Jameson), in Western Australia. *Aquaculture*, 65: 149-169.

Rose RA, Dybdahl R, Harders S (1990). Reproductive cycle of the Western Australian silverlip pearl oyster, Pinctada maxima (Jameson) (Mollusca: Pteriidae). Journal of Shellfish Research. 9 (2), 261-272.

Schiller, A., J.S. Godfrey, P.C. McIntosh, G. Meyers, & R. Fiedler. 2000. Interannual dynamics and thermodynamics of the Indo-Pacific Oceans. J. Phys. Oceanogr. 30: 987-1012.

Walker, S.J. 1999. Coupled hydrodynamic and transport models of Port Phillip Bay, a semi-enclosed bay in south-eastern Australia. *Mar. Freshwat. Res.* 50: 469-481.

10 Appendices

10.1 Appendix 1: Intellectual Property

There are no intellectual property issues associated with the materials generated during this project.

10.2 Appendix 2: Staff

Dr Anthony Hart (Department of Fisheries, Western Australia)
Dr Scott Condie (CSIRO Marine, Hobart)
Dave Murphy (Department of Fisheries, Western Australia)
Frank Fabris (Department of Fisheries, Western Australia)
Katie Weir (Department of Fisheries, Western Australia)
Jamie Colquhoun (Department of Fisheries, Western Australia)
Max Coyne (Department of Fisheries, Western Australia)
Jamin Brown (Department of Fisheries, Western Australia)

10.3 Appendix 3. Piggyback spat and pearl oyster length-frequency database

10.3.1 Introduction

The piggyback spat and pearl oyster length-frequency database is housed within a larger relational database, the Mollusc Minor Fishery and Biological Database (MBIOL), at the Research Division, Hillarys, Western Australia (Figure 10.1). The database is currently a Microsoft Access database, but is likely to be incorporated into a Division-Wide SQL relationship database in the near future.

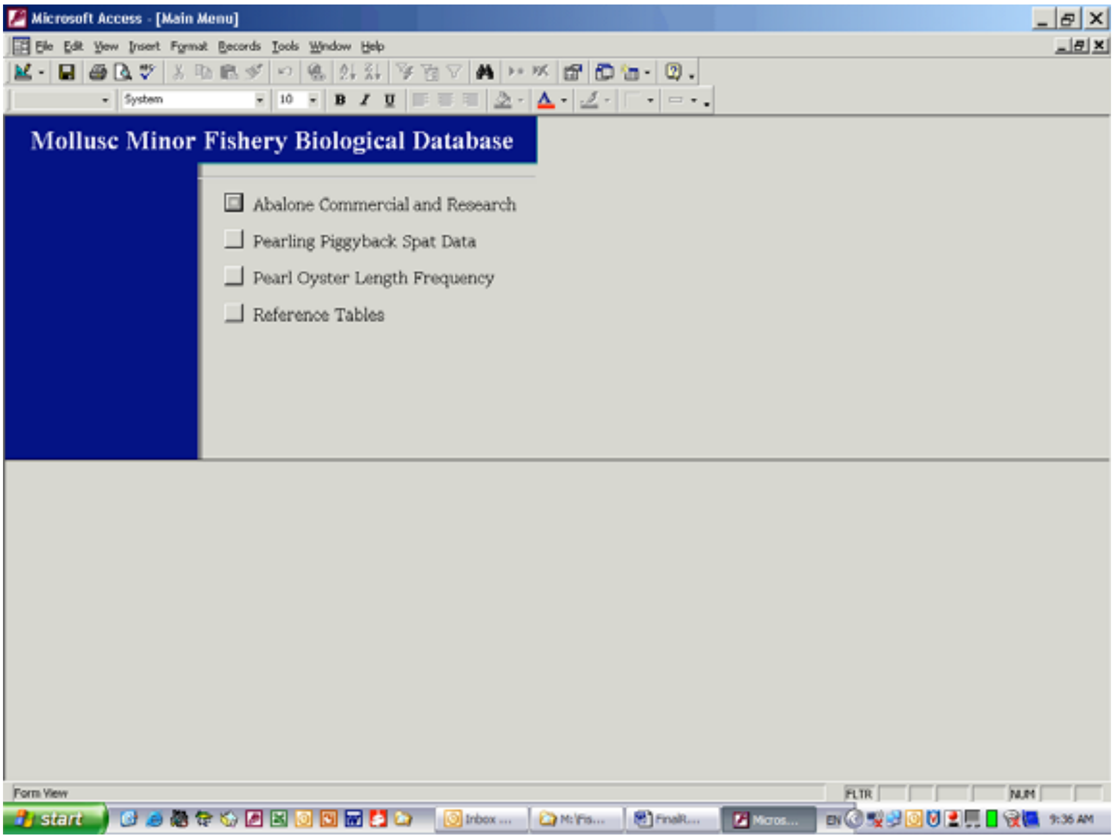


Figure 10.1 Front-end of MBIOL (Mollusc Minor Fishery and Biological Database)

10.3.2 Database Structure

The database is designed around the primary sample unit, the drift dive. The drift dive is a 40-70 minute "drift" pearl divers to catch oysters, which are then processed for spat, length-frequency, and other biological information.

10.3.2.1 Piggyback spat sampling

Figure 10.2 shows the data entry front end for spat sampling. Each drift is assigned a unique identifier (Invoice Number), which allows the data to be related to the daily catch and effort logbook database. There can be 8 drifts within a days fishing, and piggyback spat data are collected on all drifts, except 2 and 5, when length-frequency data is collected.

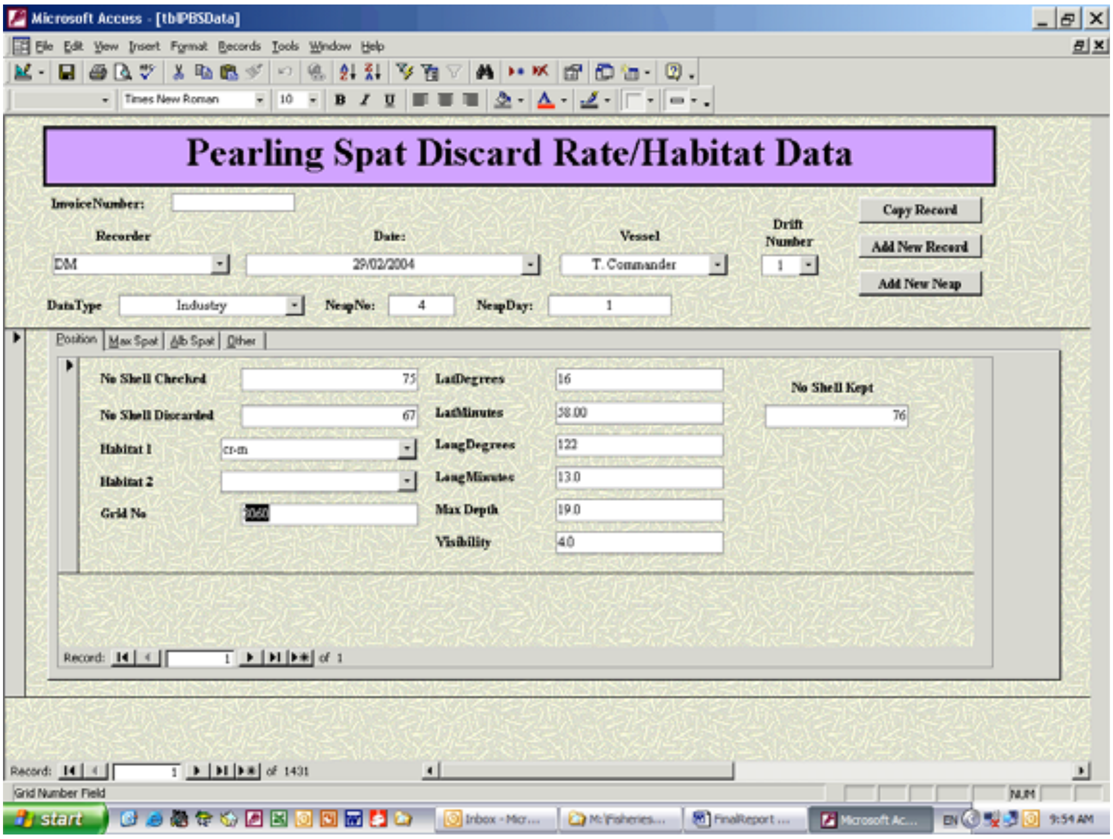


Figure 10.2 Data entry interface of the piggyback spat section of MOLBIOL (Mollusc Minor Fishery and Biological Database).

Within the main data entry table there are a number of sub-tables.

1. **Position**: records spatially important details of the location, such as GPS coordinates, number of shell checked, habitat, depth, etc..
2. **Max Spat**: records lengths of individual *P. maxima* spat, with each being assigned a unique identifier code.

3. **Alb Spat**: records lengths of individual *P. albina* spat, with each being assigned a unique identifier code
4. **Other**: records lengths of unknown spat.

10.3.2.2 Length-frequency sampling

Figure 10.3 shows the data entry front end for length-frequency sampling. Each drift is assigned a unique identifier (Invoice Number), which allows the data to be related to the daily catch and effort logbook database, and data is collected on drifts 2 and 5.

The length of each individual is assigned a size-class, rather than an exact length, and whether it is discarded ("DISCARDS") or kept ("LIVIES") is also recorded. Whether the shell is infected with boring sponge (Cliona) or not (Clean) is also recorded. This allows spatio-temporal patterns in sponge-infestation to be examined.

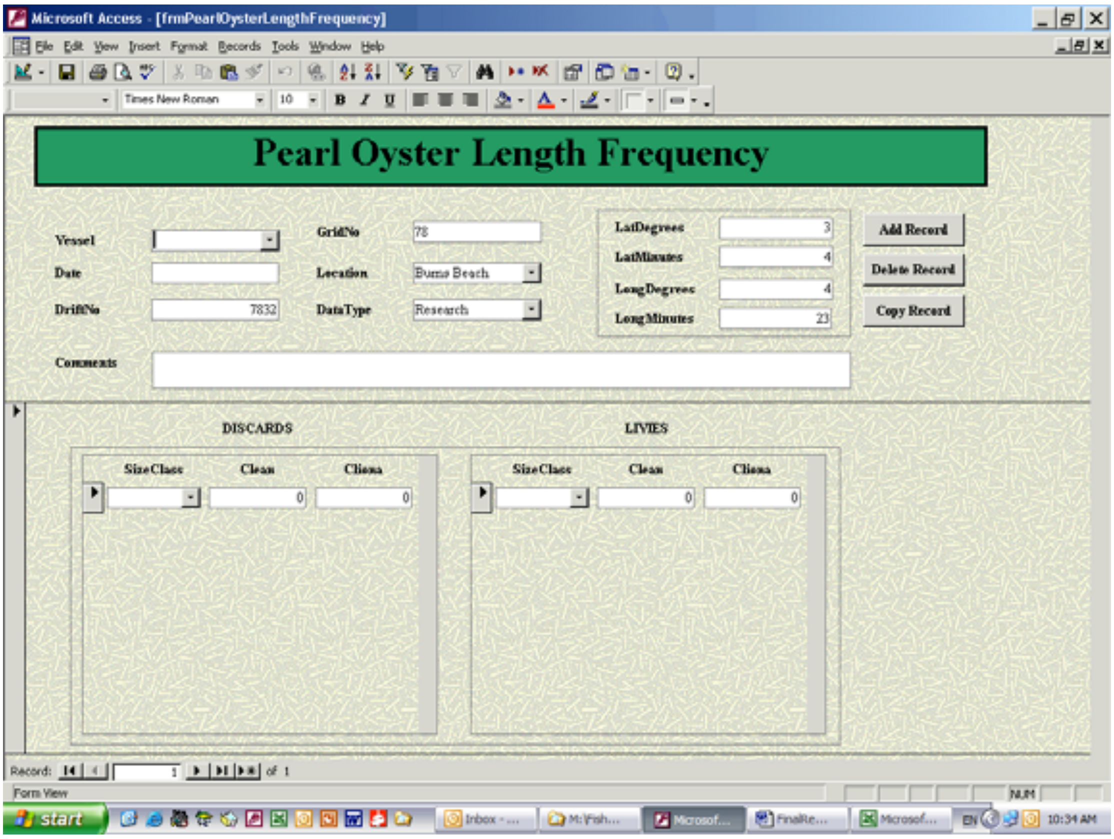


Figure 10.3 Data entry interface of the pearl oyster length-frequency section of MOLBIOL (Mollusc Minor Fishery and Biological Database).

Through various relationships back to the parent database, summary queries of piggyback spat abundance and shell-length are generated.

10.4 Appendix 4. Scientific Manuscripts arising from this project

Hart, A.M. & Joll, L.M (2006). Growth, mortality, recruitment, and sex-ratio in wild stocks of the silver-lipped pearl oyster *Pinctada maxima* (Jameson)(Mollusca: Pteriidae) in Western Australia. *Journal of Shellfish Research*. 25(1): 179 –185.

Condie, S.A., Mansbridge, J.C., Hart, A.M., Andrewartha, J.M. (2006). Transport and recruitment of silver-lip pearl oyster larvae on Australia's North West Shelf. *Journal of Shellfish Research.* 25 (1): 201-210.