Mother-of-Pearl Shell (*Pinctada maxima*): Stock Evaluation for Management and Future Harvesting in Western Australia

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Definitions and Acronyms

Unless otherwise stated, "chicken shell" refers to pre-recruits (80-119mm Dorso-Ventral Measurement [DVM]), "culture shell" refers to recruited oysters (120-174mm DVM) harvested by the fishery, and MOP (Mother-of-Pearl) refers to pearl oysters of 175mm DVM and above. These terms describe adequately the population structure of *Pinctada maxima* for the purpose of this investigation, and are commonly recognised within the industry.

1998/153 Mother of pearl (*Pinctada maxima*) shell: Stock evaluation for management and future harvesting in Western Australia

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Objectives

1. To determine growth, natural mortality and size-fecundity parameters in broodstock
2. To determine the size structure and quality of pearl stocks; focusing particularly on the distribution and abundance of Mother-of-Pearl (MOP) with respect to depth, location and historical fishing patterns
3. To determine the effects of location, depth and previous fishing pressure on the biofouling and overall quality of culture shell and MOP.
4. To undertake a preliminary assessment of the possibility of alternative methods of predicting and measuring recruitment (e.g. oceanographic or genetic studies), for establishing source-sink relationships in the pearl oyster stocks
5. To develop a protocol for setting quota of MOP based on an understanding and knowledge of broodstock/recruitment relationships in pearl oyster stocks.

Non Technical Summary

OUTCOMES ACHIEVED

Data on reproductive dynamics, growth, natural mortality, and shell quality of large *Pinctada maxima* (Mother-of-Pearl [MOP]), were synthesised with historical catch and large-scale stock survey information to provide a solid baseline of data on stock health. Research on habitat type and larval connectivity by currents is required to test hypotheses of spatial connectivity, as observed patterns showed high recruitment in areas of low adult abundance, and vice versa. An estimate of the spatial area of pearl oyster "patches" by habitat type was used with abundance data to construct an estimate of standing stock (number of shell) of MOP, and assist in developing a protocol for future sustainable harvesting.

The West Australian Pearling industry is one of Australia's most valuable aquaculture industries, currently generating around $120 - $160 million annually. The majority of pearl shell used to culture pearls come from the pearling beds in the inshore waters near Broome. The fishery for pearl oysters preferentially targets smaller (120mm - 165mm DVM) shell (hereafter defined as 'culture' shell), that are more suitable for culturing of pearls, leaving larger MOP oysters (175mm+) on the pearling grounds. These larger pearl oysters, the majority of which are female (protandric hermaphrodites), form a major component of the broodstock for the fishery. Although MOP are currently protected by the 'gauntlet' strategy adopted by the fishery, historically, MOP were harvested in large numbers to service the trade in shell buttons and other nacre products. The harvest of MOP, which occurred for most of the 20th century, was discontinued in the mid 1980's as the markets declined and the requirement for 'culture' shells (120 mm to 170mm DVM) became into the main focus. With almost 20 years of protection from fishing mortality, there has been a build up of MOP on some pearling grounds, leading to proposals to commercialise this component of the fishery.

An initial objective of this project was to gather the necessary research information to determine the feasibility of a sustainable harvest of MOP. Justification for this objective arose, in part, from the perceived need for securing a new source for large nuclei to counteract the declining source from the American Freshwater Mussel industry. If MOP could provide a viable alternative source of nuclei, there was a perceived opportunity to promote Western Australian pearls as the only cultured pearls in the world that consisted of 100% pearl oyster. However, with alternative supplies of nuclei becoming available, this objective was never actively pursued.

The primary objective of the study therefore was to conduct research into MOP stock dynamics in order to assess the sustainability of the harvest regime. In 1997, the Exmouth Gulf region of the fishery (Zone 1) was experiencing a very high exploitation rate. A review of the Zone 1 fishery highlighted a lack of knowledge of length-fecundity relationships and natural mortality rates for MOP. As a result of a high exploitation rate, it was hypothesized that the survival rate of recruits to the MOP stock may be less than the natural mortality rate of the MOP stock, thus placing a long-term risk on the breeding population. Consequently, a TAC and maximum size limit (160 mm shell length) was placed on Exmouth Gulf, and the MOP study sought to address gaps in knowledge of the stock dynamics.

Data on reproductive dynamics, growth, natural mortality, and shell quality of large *Pinctada maxima*, were obtained. Size at 50% maturity for females was confirmed to be 170-180 mm DVM. No relationship between fecundity (number of eggs) and size for oysters larger than 180mm DVM was detected, although sample size was low and needs further confirmation. Estimates of natural mortality (M) by tagging were very low (0.02-0.03), but length-converted catch-curve analyses yielded M of 0. 10 in deeper (30-34m) unfished stocks, to 0.18 in shallow (9-12m) fished areas. Thus, M appears to be negatively correlated with depth, and potentially habitat type. Growth of MOP declines from 6-7mm DVM per year for a 175-180mm DVM animal to less than 2mm per year for a 220mm DVM animal.

Shell quality of *Pinctata maxima* was significantly related to size and location, with oysters less than 150mm mostly uninfected with the boring sponge *Cliona*. Conversely, animals of 200mm+ DVM were 90% infected, with oysters from locations north of Broome showing a higher incidence of Type II category (serious) infection rate, than oysters from 80 Mile Beach. For the shell of saleable quality, a 175 mm oyster produced, on average 0.9 kg of nacre, compared to 1.2 kg of nacre for a 195 mm oyster. Conversion of caught size to packing size (following chipping of the shell margin) reduced the DVM by 8.1 % to 17.7 % of original length.
Analysis of historical catch showed some areas no longer fished, historically produced significant amounts of MOP. Catch rates of MOP (from stock surveys) on the currently fished grounds are quite high, around 60% of "culture" shell catch rate. In comparison, catch rates of MOP are 4-5 times greater on unfished grounds. MOP abundance is lower in areas north of Broome, compared to south. Recruitment appears highest in shallowest water, where density of MOP is lowest. Conversely, MOP abundance is greatest at deeper depths, where recruitment and fishing effort is lower. The most parsimonious explanation for this pattern is it reflects a higher fishing pressure on shallow inshore stocks, and thus lower recruitment into MOP stocks, without compromising recruitment. However, given that *P. maxima* are long-lived (20+ years) animals subject to low

levels of natural mortality, and have been protected for 20 years, it is also possible that shallow water MOP populations have reached equilibrium, and their lower density is reflective of quality of habitat. Note that at the handing in of this report, a CSIRO oceanographic modelling study identified source broodstock populations on the 80 Mile beach as being in shallow inshore stocks north-east of the major sink areas.

The project found that a substantial stock of MOP shell exists on the 80 Mile Beach pearling grounds. Using existing data on habitat-specific shell catchability, and area swept by a pearl diver for a standard dive hour (Joll, 1996), two estimates of the standing stock of MOP were obtained. A minimum underestimate (1,450,000 animals), which assumed there are no other grounds outside those currently fished (including Compass Rose), and a maximum estimate (2,740,000 animals), which assumed that: a) the area of unfished grounds is 30% of currently fished grounds, and b) catch rates of MOP on unfished grounds were similar to those on the lightly fished Compass Rose stocks. These estimates were used to determine a potential available annual harvest for MOP of 53,000 shell (for a minimum size of 175+mm DVM). Taking into account our lack of knowledge of the effect of harvesting on source-sink dynamics in currently fished areas, it is recommended that the take on the inshore fishing grounds be restricted to 30,000 MOP. The remaining 23,000 shell could be taken from Compass Rose.

If a decision were made to establish a MOP fishery, harvest of MOP would need to be initially restricted to the 80 Mile Beach area. North of Broome the stocks are less abundant, more infected with *Cliona*, and recruitment less regular. A legal minimum size for MOP would need to be set to separate it from the presently fished "culture" stock, and provide appropriate parameters for stock assessment. It is therefore recommended that, should a MOP harvest be deemed appropriate, an iterative harvest protocol for MOP be adopted, with initial quota set within the current 'surplus' provided by the balance between recruitment (growth) and natural mortality. Subsequent increases would be contingent on improvements in knowledge of the biology and dynamics of the oyster populations.

This project provides a scientific assessment of the stocks and the impact of proposed harvesting on those stocks. However, a decision to harvest MOP is a policy matter requiring consideration of matters beyond pure stock concerns, such as the likely impact on existing pearling licensees. Consultation with the appropriate policy and management groups is required before any MOP quotas are set.

KEYWORDS: silver-lipped pearl oyster, *Pinctada maxima*, Mother-of-Pearl, MOP, population dynamics, growth, mortality, fecundity.

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1.0 Background

The West Australian Pearling industry is Australia's most valuable aquaculture industry, currently generating around $160 - 200 million annually. The vast majority of shell used to culture pearls comes from the wild fishery predominantly off the 80 Mile Beach. Mother of Pearl shell (MOP; see section 0 for shell size definitions) are the broodstock for the wild shell populations, and are currently protected by a 'gauntlet' fishery that targets the smaller (120-174 mm DVM) 'culture' shell more suitable for culturing pearls. Concerns about the sustainability of the stock in the early 1980's resulted in harvesting of MOP being phased out by 1987 and a tightly controlled quota system being applied to the 'culture' sized stock. Without MOP harvest in the main sector of the fishery (Zone 2 and 3; Figure 1), and with the current quota system keeping the exploitation rate low, the stock in this sector is relatively secure. This area is now also the location of the only remaining significant natural source of large MOP left world wide. However, the allocation of additional quota in the Western (Zone 1) of the fishery, where recruitment is less reliable, and the 'culture' shell more heavily fished, has again raised the issue of maintaining adequate breeding stock levels for that sector of the stock.

A second major and potentially related issue that faced the Australian pearling industry at the beginning of this project, was that expanding production of large (12-20mm) high value pearls would create an increased demand for large nuclei. These larger nuclei are derived almost exclusively from one species, the washboard mussel *Megalonaias nervosa* from the USA. However, this species, along with many other freshwater mussels in the United States, was perceived to be in decline, and considered as threatened (Fassler, 1995). Thus, it was predicted that very large nuclei (12+ mm) may become unobtainable, in spite of the high demand. In response, the West Australian Pearl Industry commissioned a research project investigating the potential of MOP as a source of large nuclei (Scoones, 1999), noting that previous limited trials of MOP nuclei have been successful. It was proposed that the MOP resource, while necessary to sustain the stock, could also be subject to a low level harvesting quota to provide a unique source of large, genuine pearl nuclei.

The purpose of this project was to conduct an examination of stock levels of pearl oysters in Western Australia, with special regard to MOP, and to develop an improved understanding of biological parameters important to this component of the stock. The project was established to allow the biology and degree of exploitation of the MOP resource to be appropriately considered in the management of the pearl oyster fishery.

2.0 Need

The three year study was proposed to examine basic biological data relevant to the MOP component of pearl stocks off the West Australian coast, and the need arose from a number of directions. Firstly, the Exmouth Gulf region of the fishery (Zone 1) was experiencing a very high exploitation rate. In a review of the Zone 1 fishery in 1997, a lack of knowledge of length-fecundity relationships and natural mortality rates for MOP was highlighted. As a result of a high exploitation rate, it was hypothesized that the survival rate of recruits to the MOP stock may be less than the natural mortality rate of the MOP stock, thus placing a long-term risk on the breeding population. Therefore research into MOP stock dynamics was identified to be of critical importance to maintaining the sustainability of the harvest regime in Zone 1.

Initially (in 1997), there was a perceived long-term strategic need to find an alternative supply of large nuclei to counteract the declining source from the American Freshwater Mussel industry. In anticipation of demands for harvesting of MOP for nuclei, this translated into a need to start gathering information to determine a sustainable harvesting regime for MOP. The uncertainties to be addressed were as follows. First, what is the extent of MOP stocks with respect to overall numbers of pearl shell. Secondly, what are the rates of recruitment into, and natural mortality of, the MOP stocks. These data, combined with knowledge of stock size, particularly with reference to the culture shell, will enable rates of sustainable harvest to be estimated. Finally, what is the impact of harvesting of MOP on recruitment? Since the mid-1990s there have been large increases in catch rates at two spatially distinct areas, 80 Mile Beach and the Lacepede Islands. Whether this has been environmentally and/or stock driven is currently undetermined, although recent data suggests that an environmental factor significantly effects recruitment in the central area (Zones 2/3) of the fishery (Hart et al., 1999).

An initial identified strategy for sustainable management of MOP was relocation of MOP to better growth areas. Obviously the quality of MOP shell will determine the amount of nuclei that can be produced. There is some anecdotal information suggesting that MOP shell from different areas have different quality of shell, and there is the possibility that shell growth and quality may be improved by transplanting to these areas. Ultimately, after establishing the parameters for natural mortality, fecundity, and recruitment in MOP populations, there is the potential to undertake: a) a one-off, large-scale stock survey of MOP, and b) investigate the possibility of re-locating hatchery produced shell, after they have grown too large for culturing pearls, into areas to grow to a suitable MOP size.

After this project commenced, the need to translocate MOP to better growth areas was re-evaluated, found to be unsubstantiated, and the proposed work subject to unacceptable health risks (i.e. from bioeroding sponge infection). This re-evaluation precipitated a review of the project objectives in consultation with industry (see section 2.1).

2.1 Objectives

The Initial Objectives:

1. To determine growth, natural mortality, and size-fecundity parameters in MOP.

2. To determine the distribution and abundance of ‘nuclei quality’ MOP.

3. To determine the effects of location and depth on the biofouling and overall quality of MOP.
4. To undertake a preliminary assessment of the effects on growth and mortality, of transplanting MOP to quality areas.
5. To develop a protocol for setting quota of MOP.

Early on in the project there were concerns over support by Industry collaborators for sections of this research, problems in making assessments while on industry vessels (in conjunction with fishing) and moves by Industry to restructure and alter the objectives. The project objectives were revised (with industry consultation) and the Principal Investigator, Dr Anthony Hart advised FRDC of changes in May 1999.

Revised Objectives:

1. To determine growth, natural mortality and size-fecundity parameters in broodstock
2. To determine the size structure and quality of pearl stocks; focusing particularly on the distribution and abundance of MOP with respect to depth, location and historical fishing patterns
3. To determine the effects of location, depth and previous fishing pressure on the biofouling and overall quality of culture shell and MOP.
4. To undertake a preliminary assessment of the possibility of alternative methods of predicting and measuring recruitment (e.g. oceanographic or genetic studies), for establishing source-sink relationships in the pearl oyster stocks
5. To develop a protocol for setting quota of MOP based on an understanding and knowledge of broodstock/recruitment relationships in pearl oyster stocks.

The changes in project emphasis included more information on the complete range of mature pearl oysters (use of broodstock instead of MOP), and closer scrutiny of general population assessment and examination of fishing effects. One initial objective, No.4, which related to the transplanting of MOP to improve growth and quality of shell, was replaced. This objective was removed as it was seen as a highly speculative with considerable logistical and disease issues. In particular, if ‘quality’ areas were identified, transplant experiments could possibly introduce agents responsible for poor quality shell into good quality areas.

The set-up of trial MOP farming plots in areas identified to produce good quality MOP, was replaced with a literature review of methods of predicting and measuring recruitment for establishing source-sink relationships in the pearl oyster stocks. This desktop study links well with the current FRDC project (2000/127) which is looking at recruitment in the Western Australian pearl oyster fishery

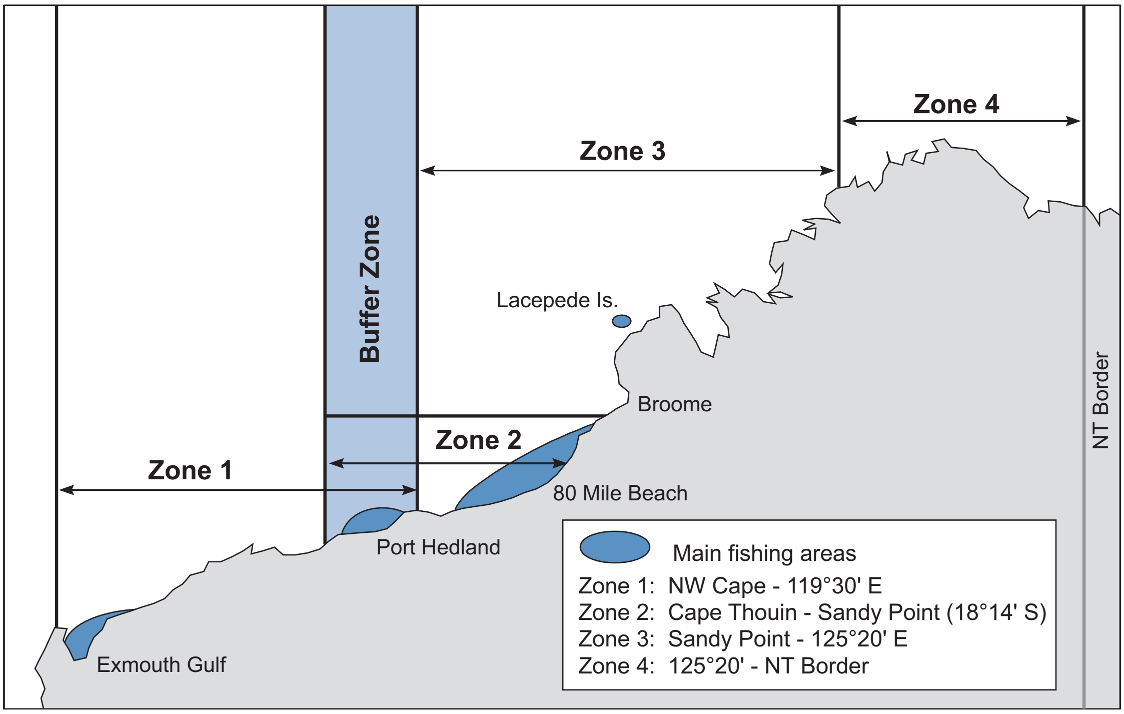


Figure 1. Management areas of the Western Australian *Pinctada maxima* fishery. The buffer zone is the area in which license holders in both Zone 1 and Zone 2 may harvest pearl shell.

3.0 Methods

3.1 Growth and Natural Mortality

Between 1998 and 2000 MOP growth was assessed while conducting mortality experiments at 80 Mile Beach, and at Gales Bay in Exmouth Gulf. In 1998, 510 oysters were tagged on the 80 Mile Beach pearling grounds and over 960 oysters were tagged in Exmouth Gulf in 1998 and 1999. Additional data on growth of MOP was sourced from previous FRDC funded research carried out at the 80 Mile Beach, Lacepede Islands and Exmouth Gulf (Hart et al., 1999; Joll, 1996). All releases and recaptures were made during a single neap in June of each year at the 80 Mile Beach site, during a single neap in February/March each year at the Lacepede Channel site and during a single neap in June/July each year at the Exmouth Gulf site.

Pearl oysters to be tagged were obtained from commercially fished by-catch (both undersize, <120 mm DVM and oversize, >170 mm DVM) and from oysters caught during research diving (full size range including culture-sized shell). Prior to measurement and tagging, oysters were held in plastic holding crates hung from the side of the boat or aerated seawater on deck (<4 hours) or when available in purpose built seawater through-flow tanks on pearling boats (up to 12 hours).

Oysters were tagged using plastic shellfish tags (Hallprint®, South Australia) measuring approximately 15 x 7 mm (7 x 3 mm for smaller oysters < 50 mm DVM). These tags were applied to the left and right valves of each oyster using a cyano-acrylate glue (Selleys® or Loctite® 454 Gel). Each oyster was tagged using a pair of tags with the same 4 character identifier. Following tagging, the dorso-ventral measurement (DVM) of each oyster was recorded using standard calipers and measuring boards. Other morphometric measurements (anterior-posterior, hinge line, hinge depth and thickness) were taken, but only the DVM results are reported here.

All oysters collected were placed out on pearl oyster habitat characteristic of each region. At the 80 Mile Beach site and Lacepede Channel oysters were placed out on substrate at about 15 -

18 m depth, at Exmouth Gulf oysters were fished and replaced at a depth of about 5 m. Oyster recaptured oysters during research surveys were re-measured in successive years and re-released in the same area. Any new pearl oysters taken during the re-captures were tagged, measured and released along with the recaptured oysters. During the period of growth monitoring, the pearling industry avoided fishing in the vicinity of tag sites. This enabled estimates of natural mortality to be made by measuring annual survival.

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

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

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

The data came from capture-recapture experiments with unknown age, hence Fabens method was used to estimate the growth parameters.

$$\Delta l_i = (L_\infty - l_i)\left(1 - e^{-K\Delta t_i}\right) + \varepsilon_i \tag{2}$$

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

3.1.1 Mortality estimates

Mortality was determined by two methods. Directly, by tag and recapture studies conducted on fixed transect lines, indirectly by examining stock structure and undertaking length converted catch-curve analysis (Pauly, 1984). The majority (96%) of oysters used in the mortality experiment were 170 – 220mm DVM. Experiments were initially set-up at 80 Mile Beach and Exmouth Gulf, however no data were obtained from the 80 Mile Beach site, as it could not be relocated. Thus, estimates of mortality from 80 Mile Beach are only available from catch-curve analysis.

3.1.2 Mortality estimates from tagging

Estimates were obtained by monitoring a known quantity of MOP in a pre-defined grid area, and counting the total number of live animals remaining at successive time intervals. Rates of mortality were estimated as a % of total number per year.

A study site was established in the Gales Bay area of Exmouth Gulf in July 1998, at a depth of 6 metres. A series of 5 parallel lines were laid on the seabed secured at the ends with anchors. Short lengths of chain were attached to the rope at regular intervals to assist in anchoring the line to the bottom. The lines were laid out in a north-south direction approximately 10 metres apart and numbered 1 to 5 from east to west. Oysters were collected by drift diving, brought to the surface and placed in baskets suspended in the water from the side of the boat. On board an area on the shell was prepared for the tags, the tags were fixed to the shell using "Loctite 454 Gel super glue" (cyanoacrylate adhesive) and then two measurements were recorded (DVM and maximum thickness). The number of shell collected, processed and placed on the bottom each time was minimised (approximately 40-50), to ensure the pearl oysters were stressed as little as possible from the catch and tag procedure. Oysters were then hand placed on the substrate next to one of the five lines on the seabed. Between July 3 - 11 1998, 267 oysters were tagged and placed next to lines 1 and 2, with a further 464 oysters being tagged during the period 15 - 29 August 1998. Oysters were tagged in the size range from 60 mm to 240 mm DVM, with over 75% of the shell being in the size range 170 mm to 230 mm.

To separate natural mortality from experimental mortality (oysters stressed by the collection and translocation to experimental sites), oysters were allowed to recover for one month after the initial tag and release. Mortality was estimated for the one-month period, after which the estimation of natural mortality began. It was assumed stressed shell would either have died or recovered to a naturally healthy state.

The intention was to collect survival and growth data after pearl oysters had been at liberty for one and two years (August 1999 and 2000). However, it was during the first assessment of the experiment (August 1999) that the destructive effects of a category 5 Cyclone (Vance, 22 March 1999) became apparent. Experimental lines suffered a similar fate to equipment on nearby commercial farms (Exmouth Pearls), where rainfall (395 mm), run-off, winds and storm surge had caused widespread movement of oysters and equipment. Although the overall survival rate of shell seemed high, as a large number of pearl oysters where found live (n = 221, 48 %), there was no discernable structure left to the experimental layout and it was not possible to collect mortality data (experimental lines and oysters had been moved in a haphazard way).

As a consequence of Cyclone Vance, a further two small experiments were set-up at Gales Bay on the 8 August 1999 to determine survival of shell over a single year period. In the first experiment, seven subsets of 20 tagged MOP shell were positioned by divers along four 50 m longlines (Figure 2). Tagged oysters were spaced approx 0.8 metre apart in close proximity to the weighted longlines which were spaced > 5 m apart. This was essentially a repeat of the initial mortality experiment. However, as a consequence result of Cyclone Vance destroying the first experiment, we sought to understand what survival might be in a stressful situation with shells being randomly turned over and so forth. In the second experiment, shells of similar size were placed in 8 piles of 10 pearl oysters along a separate benthic longline, without care for shell positioning within the pile (e.g. many shells were upside down or piled atop each other). Both experiment sites were revisited a year later when divers retrieved, recorded and measured the tagged oysters. This enabled an assessment of mortality between MOP shells that were handled carefully, compared to those “dumped” haphazardly as might occur during a cyclone or fishing operation.

3.1.3 Catch curve analysis

To interpret growth data in terms of age, an age-length key was generated using the method described by Haddon (2001). Age–length keys were generated from the parameters of the von Bertalanffy growth equation, with variations of age at length obtained from the residuals in the tag-recapture model fitting (Haddon 2001). Survey lengths (see Section 4.6 and 4.7) from the Lacepede Islands (2 locations: Lacepede Channel and Hama Patch) and 80 Mile Beach (5 locations: Patterson Shoal, 10 Mile, 13-15 Mile, 17 Mile, Compass Rose) were allocated to ages using proportions in the age length key. No model was run for oysters in Exmouth Gulf as there was no detailed survey of these stocks to provide length frequency information.

Natural mortality of MOP shell (= total mortality or Z) was assessed by determining the negative slope of the regression line from log frequency estimates of numbers at age for those shells of MOP age. This is the length-converetd catch-curve procedure described by Pauly (1984). Mortality was estimated for 4 locations (Lacepede Islands [180mm DVM = age 6+]; 80 Mile Beach Inshore [180mm = age 8+]; 80 Mile Beach Offshore [8+ age]; Compass Rose [8+ age]).

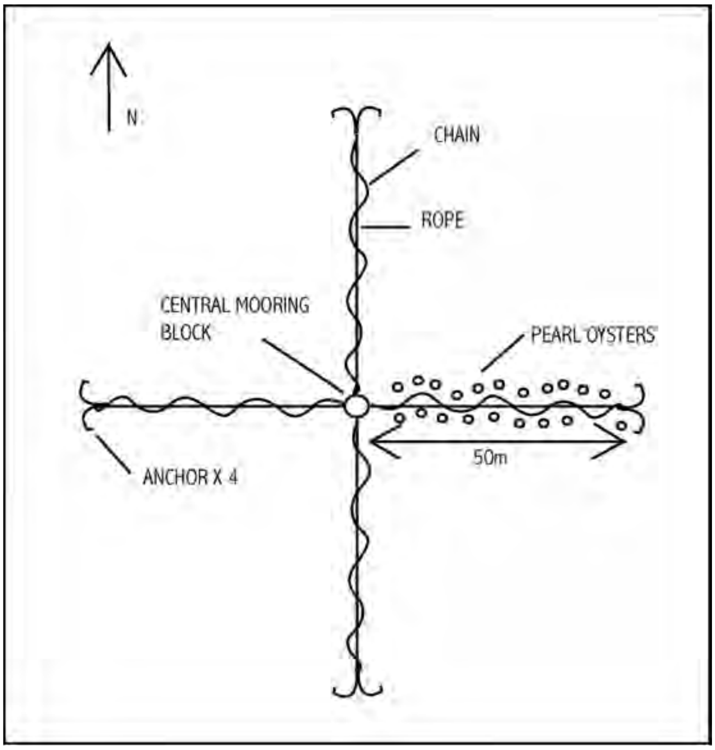


Figure 2. Layout of study site in Gales Bay, Exmouth.

3.2 Sex Ratio, Gonad Development and Size Fecundity

3.2.1 Study Sites and Data Collection

Rose et al., (1990) and Hancock (1993) quantified the reproductive cycle of wild stocks of *Pinctada maxima* in Western Australia, and our sampling utilised this knowledge. To coincide with the beginning of the predicted spawning season (Oct-Dec on 80 Mile Beach; Dec-Jan in Exmouth Gulf), sex ratio (n = 479), gonad development (n = 70) and size-fecundity were (n = 12) examined from oysters collected from 80 Mile Beach in October 1998 and Exmouth Gulf in January 1999. Data collection for reproductive samples followed similar methods to growth and mortality experiments.

The initial trip to 80 Mile Beach (October, 1998) yielded no oyster gonads of sufficient development to enable egg counts. Similarly, only 13 MOP oysters from the 70 samples collected at Exmouth Gulf were at gonad stage 4 (Table 1), and could be used for fecundity estimates. Subsequently, a sample of 10 × stage 4 gonads from Hancock's (1993) study at Exmouth Gulf and Broome, which had been fixated in formalin at the West Australian Marine Research Laboratories, were used to supplement the Exmouth Gulf samples. This resulted in a sample of 38 oysters for size-fecundity analysis.

DVM of all specimens was recorded and the valves of each oyster were partially opened to inspect gonad condition and determine sex; sex was determined by gonad colour (males - white to cream coloured gonad, females - pale yellow to orange coloured gonad). Animals in which the gonad was a watery white colour or appeared translucent were recorded as indeterminate. After measuring and sexing the oysters, males were released back into the water while females were dissected. The flat valve was removed to expose the body tissues and the visceral mass (containing gonad) was dissected away from the muscle and placed in 10% formalin and seawater within a labelled sample jar.

3.2.2 Gonad extractions and egg counts – Exmouth Gulf samples

In the laboratory the visceral mass samples were removed from the formalin solution in a fume cupboard, washed and placed in 70% ethanol. When all the specimens had been transferred to ethanol a visually determined ‘stage’ of gonad development was assigned to each specimen (Table 1). The staging criteria used in this process was a modified version of the criteria developed by Tranter (1958) and used by Rose et al. (1990). The assigned stage was dependent upon the texture or graininess of the gonad and/or the amount of spread of the gonad compared to an oyster in spawning condition.

Gonads from 70 specimens were separated from visceral matter under a dissecting microscope. This proved to be a difficult and time-consuming process due to the gonad not being a discrete organ. Each sample was cut into sections of approximately 0.5mm thickness from which gonad tissue was separated from visceral tissue. Microscopic dissection was required to separate the remaining gonad from the viscera using fine brushes and pipettes of 70% ethanol. The separated gonad and viscera were dried at 90^{o}C in an oven for three hours. Both the gonad and viscera dry weights were recorded immediately on removal from the oven, providing an instantaneous standard dry weight.

Gonad weights and egg counts were undertaken using the following procedure:

1) Three small sub-samples were incised from each of the Stage 4 gonads (n = 12) and weighed.
2) Sub-samples were rehydrated in 10ml and eggs teased apart using a small stiff paint brush and probes.
3) The 10ml samples were agitated to accomplish uniform mixing of eggs in solution
4) 3 × 200µl aliquot samples of the mixture were extracted and placed in three chambers of a perspex counting plate.
5) Eggs were counted using a graticule (10 x 10mm), and the average of the three counts were scaled up to a total egg count per 0.001g of dry gonad. These were converted to a total egg count per gonad specimen (see Equation 2).
6) The egg counts for the 12 specimens were used to investigate fecundity and size relationships.

3.2.3 Egg counts – Hancock (1993) samples

A second study was conducted to estimate the volume of gonad material and potential number and size of oocytes from “fixed” oysters (formalin to alcohol) within MOP size classes. Samples for this study originated from oysters collected in Exmouth and Broome during a previous study on reproduction of *Pinctada maxima* (Hancock, 1993). Only “late developing” (stage 4) condition females of (Hancock 1993) were examined, so as to provide comparability with Exmouth Gulf samples.

Table 1. Gonad developmental stage of *Pinctada maxima* (modified from Tranter 1958)

Developmental Stage	Description
1.	Discrete area of gonad distinguishable at the base of the gut loop. No gonad development on the gut loop but gonad colour clearly indicates female.
2.	A small area of gonad appears on one side of the gut loop (anterior left hand surface).
3.	The gonad extends continuously along both sides of the gut loop and appears fine grain in texture but not bulging.
4.	Gonadal tissue covers much of the visible surface of the stomach, digestive gland and gut loop. The texture is smooth and the gonad is bulging compared to surrounding tissue.

An examination procedure to macroscopically analyse the spatial area and volume of gonad found within the viscera of pearl oysters was developed (A. Hancock, pers. comm.). To reveal the area taken up by gonad material, the visceral mass of 10 × Stage 4 gonads (formalin fixed) was cut into transverse 5mm serial sections with a grade 22 scalpel, resulting in between 9 and 12 sections, depending on the size of the viscera. Each section was placed in a petri dish under a dissecting microscope and a camera connected to a Macintosh computer captured images of each section. Using a measuring package ("NIH Image" software), a measure of the total area of somatic and gonad tissue was determined. The equation for estimating gonad volume was

$$V_i = \sum_{1}^{n} G_{ij} \times 5\ mm \tag{3}$$

where V_i is the volume (mm^3) of gonad in sample i, n is the number of sections, G_{ij} is the area (in mm^2 – determined by NIH software) of gonad in section j of sample i. The 5 mm multiplier indicates the width between individual sections. This formula does not calculate exact volumes because of the assumption that gonad area is uniform within the 5mm sections, but was deemed sufficiently accurate for comparative purposes.

Determination of fecundity in these animals required estimates of the diameter of an individual oocyte, and the area within a gonad occupied by free oocytes. Hancock (1993) established that proportion of area taken up by oocytes within the gonad was 0.35. Oocyte diameters ($n = 20$ oocytes per sample) from 12 sample slides (each slide was a gonad section from different oysters) of “late developing” (Hancock stage 4) and 12 samples of “spawning ripe” (Hancock stage 5) gonads were measured with “NIH Image” software connected to a compound microscope.

3.2.4 Data Analysis

Estimates of total fecundity (total number of eggs per gonad) were obtained from each method with the following equations.

Dried Samples

$$F_i = \frac{W_i}{0.001} \times C_i \tag{4}$$

where F_i is the fecundity (no. of eggs) of specimen i, W_i is the entire gonad weight (g) of specimen i, C_i is the count of eggs per 0.001 g of gonad in specimen i.

Fixed samples

$$F_i = \frac{V_i \times 0.3}{\frac{4}{3}\Pi r^3} \qquad (5)$$

where F_i is the fecundity (no. of eggs) of specimen *i*, V_i is the volume of gonad (mm^3) in specimen *i*, 0.3 is the average proportion of gonad volume occupied from free oocytes (from Hancock, 1993), *r* is the mean radius of individual oocytes. The assumption here is that eggs are perfectly spherical.

3.3 Assessment of Historical Fishing Patterns

General information about the MOP fishery are well documented but the lack of availability of positioning systems and standard formats for catch reporting meant that there was little definitive, quantitative data available on where catches were made. The only well documented surveys of pearl fisheries were the voyages of the Paxie (1956 – early 60's) and a Fisheries Department prawn / pearl survey in 1987 (Penn and Dybdhal, 1988). Archival data that includes annual tonnages of MOP shell taken from WA waters was also examined to provide an overview of the fishery from the 1890's onwards.

During 1978 a research logbook was introduced to the fishery, with all vessels completing the logbook by the start of the 1982 season. Examination of the total number of shell collected, the percentage of shell that were MOP and the average number of MOP shell collected per dive hour for post 1978 records was used to produce distribution and abundance summaries for the years 1978 - 1981 (only partial data available) and 1982 - 1986.

Summaries of pearl catch, effort and catch rates between 1995 and 1999 at the main fishing grids were also made so as to identify the most productive areas of the fishery.

3.4 Stock Surveys

3.4.1 Pilot Industry Survey

During 24-28th February 1999, a preliminary survey was conducted aboard the vessel "Joseph Conrad", in the Lacepede Channel area. The objectives of the survey were to trial proposed sampling methods for surveying MOP stocks in conjunction with commercial fishing operations, and to obtain preliminary estimates of MOP shell quality (biofouling and *Cliona* infection rates).

Two data collection techniques were tested;

- One nominated drift per day, where each diver collected all (or as many as possible) pearl shell seen, of a minimum size of 120mm (the legal minimum) and above, and
- Three nominated drifts per day where each diver attempted to collect 10 MOP shell consecutively at some point during the drift.

Shell measurements, inspection for the boring sponge, *Cliona*, interviews with divers and abundance counts allowed assessment of the stock sampling strategy and collection of length frequency and shell condition information.

3.4.2 Gantheuame - Lacepede Pearling Ground Survey

A research survey of pearling ground north of Broome, from deepwater Gantheuame in the south to the Baleine Banks north of the Lacepede Channel area, was conducted aboard the vessel Laveque

Trader, between the 13-21st of November 1999 (Figure 3). Four divers undertook between 3 and 6 survey drifts at seven locations in two broad depths (Figure 5a). Two locations are commercially fished (Lacepede Channel and Hama Patch). The other locations were selected from past survey notes (Paxie surveys 1950 –60's) and private survey notes supplied by industry skippers.

The sampling relied on normal drift diving protocols, i.e. the Laveque Trader fished along prevailing longshore currents and divers collected all pearl oysters seen. DVM and hinge measurements were taken and shells assessed for the level of *Cliona* (boring sponge) infection. Level of infection was graded to three subjective levels; no infection (0), low level or inactive infection visible by pitting and a low level of shell damage – (level I) and medium to high level infections which caused structural damage to the shell (level II) (Figure 7). All pearl oysters of culture size and below (<175mm DVM) were returned to the water live.

3.4.3 80 Mile Beach Pearling Ground Survey

A research survey of the most productive pearling grounds was conducted aboard the vessel *Dalumba* between the 10-16th of September 2001. Five commercial pearl divers surveyed sites along 80 Mile Beach (10-20m) and Compass Rose (30-34 m) (Figure 4).

At the shallow water pearling grounds, the locations were 5-8 Mile, the 10 Mile, the 13-15 Mile and the 17 Mile (Figure 4). At each location, 3 sites were selected, "Inshore" (9-11 m depth), that reflected pearling grounds in the shallow areas inshore, "Midshore" (13-15 m) and Offshore (15-17 m). At each of the 3 sites 3 replicate drifts were made with 5 divers. Due to time limitations, no offshore site was sampled at the 17 mile and one diver was absent on the third dive at the 5-8 mile offshore site.

Divers collected all pearl oysters seen, but within a dive, were instructed to take 3 sub-samples along the dive, with divers loading the catch from the first, second and third sector of the dive in separate marked catch bags on their main holding lines. This enabled 'onshore – offshore' depth trends from within drifts to be examined.

At the deepwater pearling grounds (Compass Rose), only 3 divers collected pearl oysters because of depth constraints. Sites within the Compass Rose were also termed "inshore", "midshore" and "offshore" as they were found at increasing depths from the shallowest site in the east to the deeper offshore site in the west. At the inshore sites and midshore sites, 3 and 4 dives were made respectively. At the deepest site, safety precautions meant that diving could only take place on the lowest tides (shallowest time to dive) and only 2 replicate dives were made.

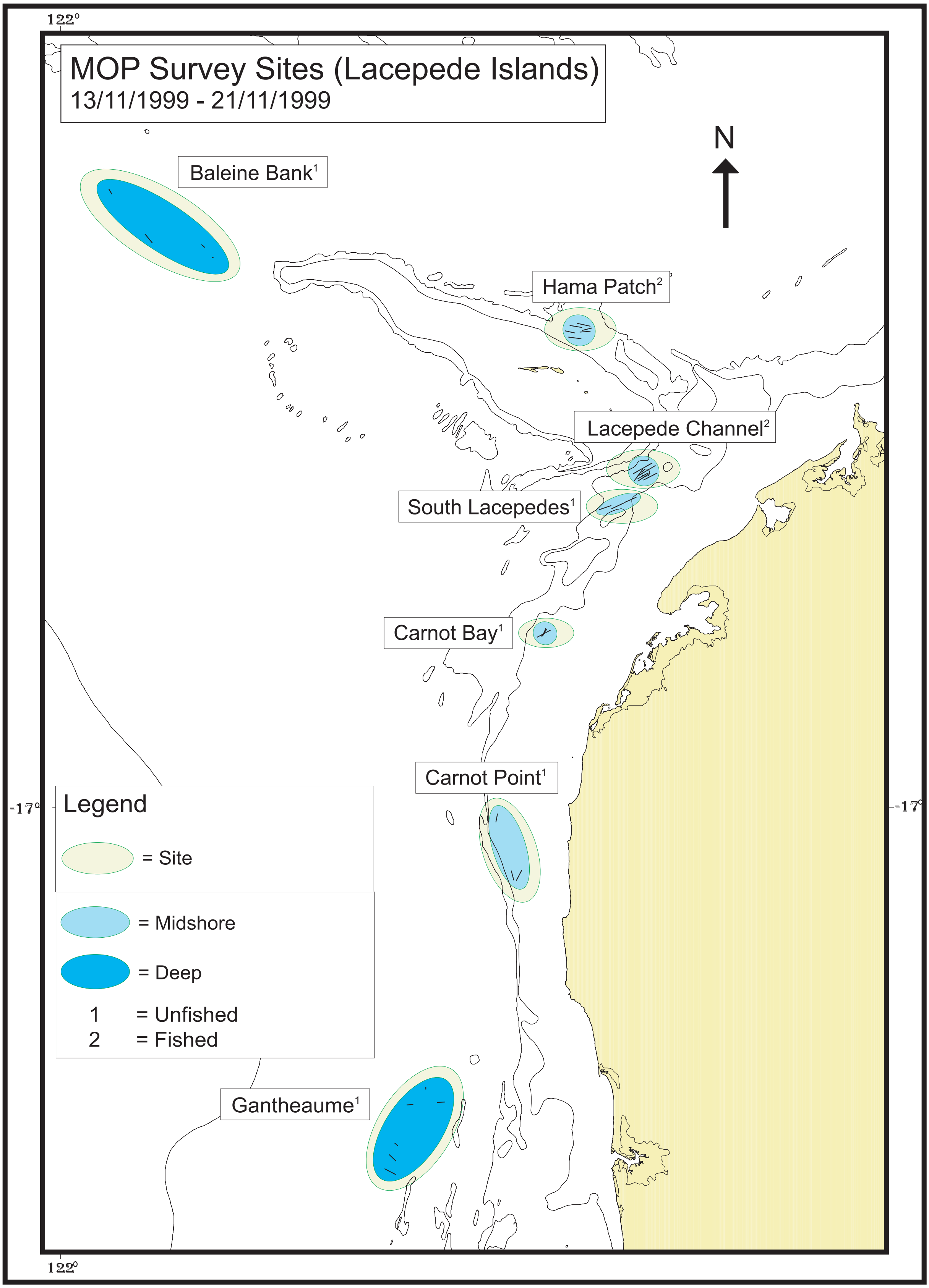


Figure 3. North of Broome Survey Site. Lines within sites represent pearl drifts and are accurate to scale.

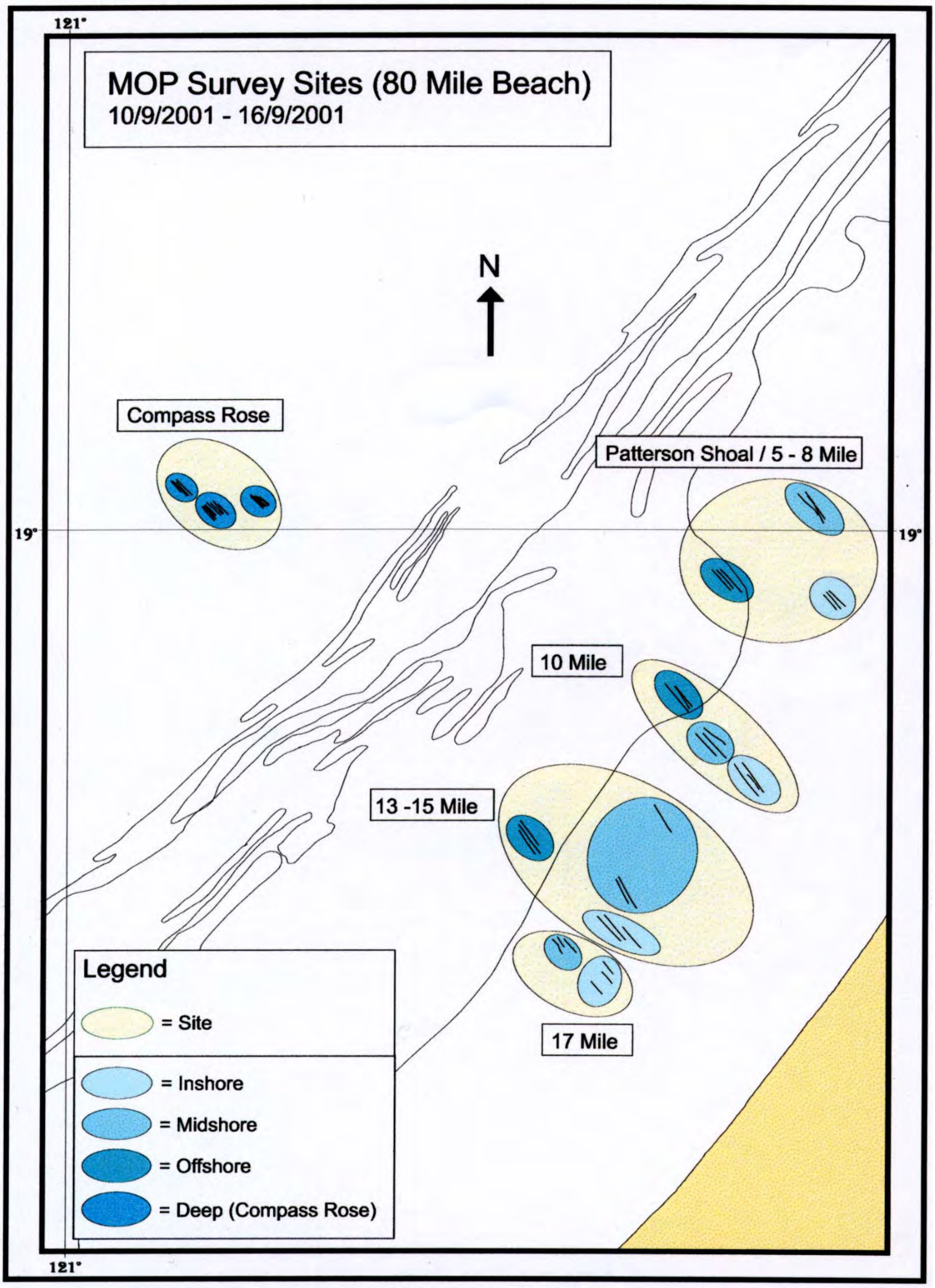


Figure 4. 80 Mile Beach Survey Site. Lines within sites represent pearl drifts and are accurate to scale.

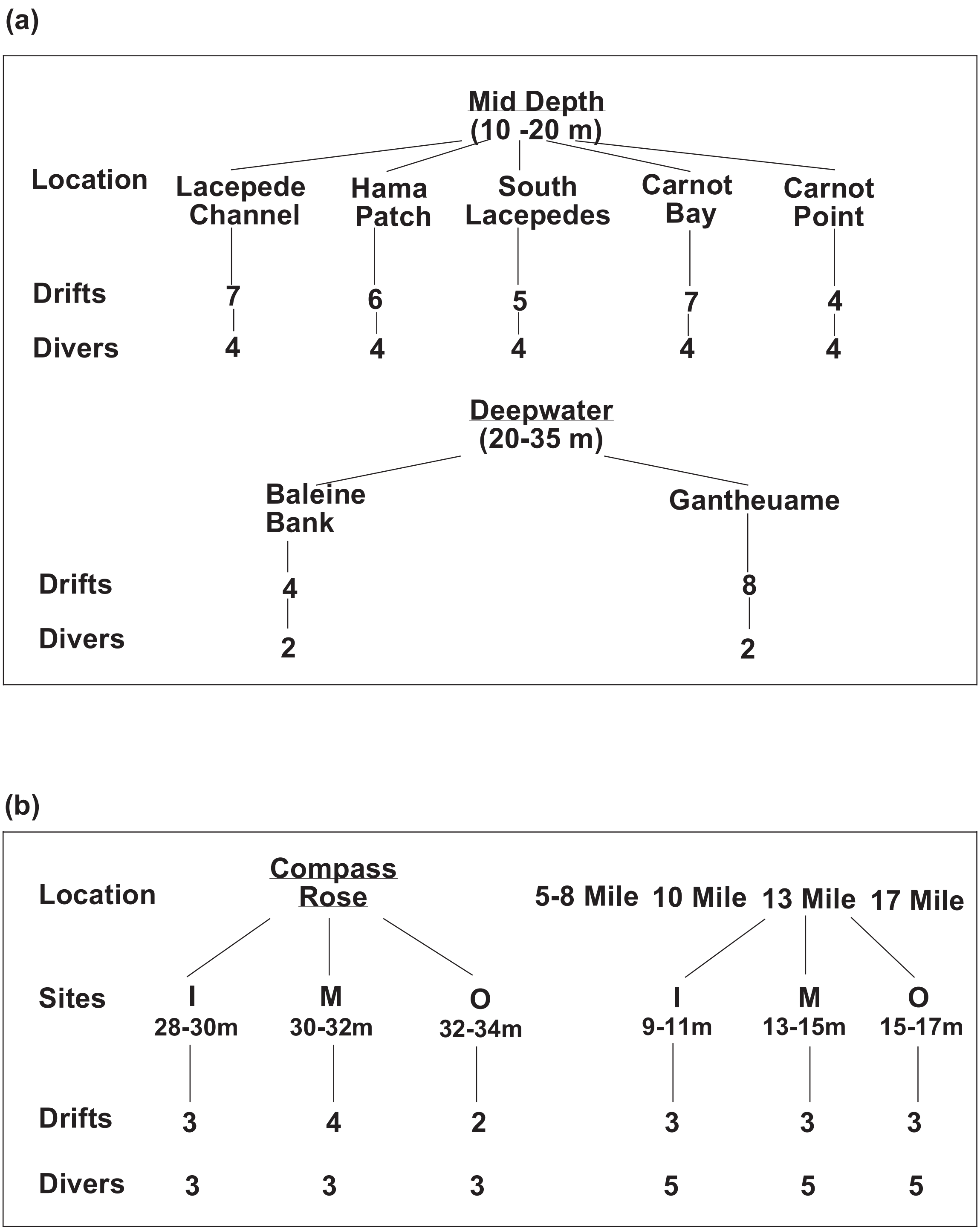


Figure 5. **Sampling design for *Pinctada maxima* stock surveys a) North of Broome (November 1999) and b) 80 Mile Beach pearl stocks (September 2001). In b), I, M, O, at Sites refers to inshore, midshore, and offshore habitats. Depth ranges for each of these strata are given.**

All pearl oysters caught by divers were brought on-board and measured (DVM and hinge; Figure 6) and assessed for *Cliona* as in the pilot survey (Figure 7). Sampling procedures involving video surveys of the benthos were tested. Divers holding video cameras while on normal "drifts" attempted to record information on abundance of shell and information on the quality of shell and habitat of benthos.

3.4.4 Data analysis

Number of pearl oysters caught was divided into undersized (<120mm DVM), culture (120 – 175 mm DVM) and mother of pearl (>175mm DVM) size classes for analysis purposes. Spatial variation in catch rate and size (mm) by locations, depth (Inshore, mid-shore, offshore), and divers was examined by ANOVA. Significant differences among means were identified using Tukey's test for equal or unequal sample size (n).

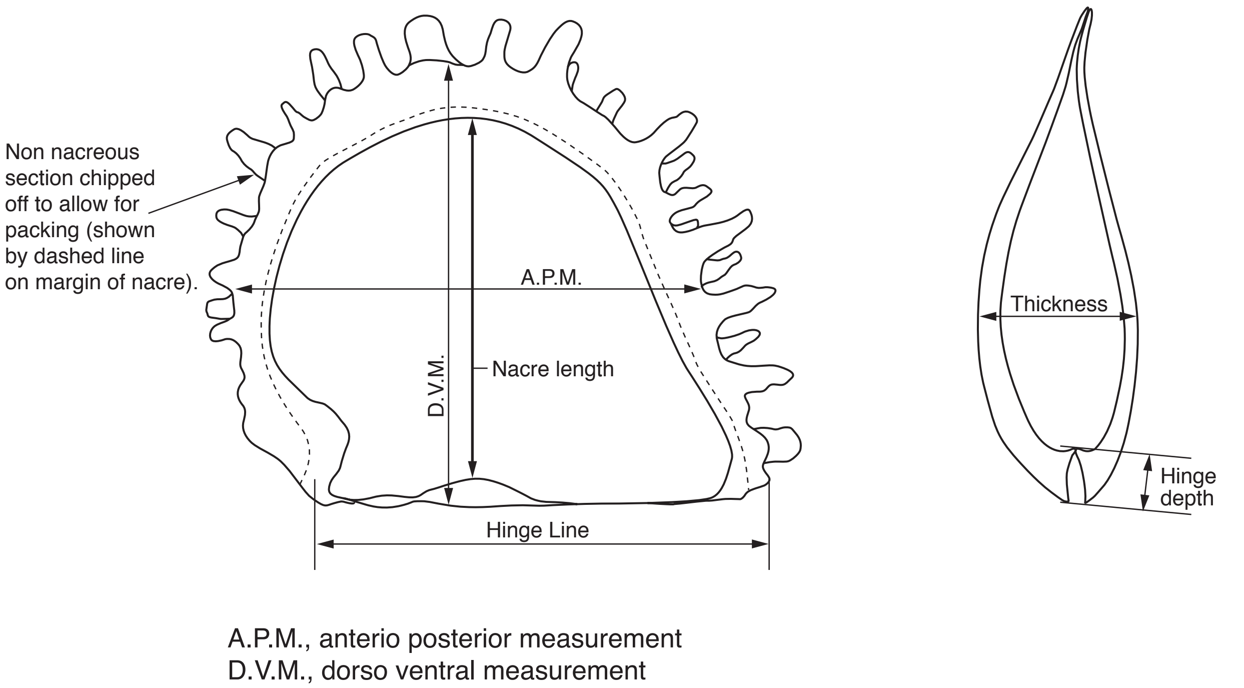


Figure 6. Morphometric measurements commonly used to measure the morphology of *Pinctada maxima*. DVM is the principal measure of growth.

3.5 Assessment of MOP shell quality

MOP shell quality was assessed with two indicators: 1) the level of boring sponge (*Cliona)* infection rate; 2) MOP of saleable quality, determined from visual inspection for quality (based on level of *cliona*, worm, and boring mussel) by pearl fishers. A *cliona* infection grade category was also developed (Figure 7). Processing of shell of saleable quality was carried out in the following manner.

1) The margins of sacrificed shells were removed (chipped off) to reduce packing size and weight of shells sold.
2) The length of nacre and weight of each shell valve were recorded to determine recovery weights.
3) MOP shell valves were sorted into three commercial grades (B, FAQ, and C) on board the fishing vessels. "B" is the sought after high grade shell, "FAQ" is the "Frequently Asked Question" shell, whose quality is suspect, and "C" grade is the unwanted low-grade shell.

Ratios of *Cliona* infection was compared among sites and shell size groups using CHI- square tests.

3.6 Measuring source-sink relationships in *Pinctada maxima* stocks

Source-sink theory has become a tool for understanding how the dispersal of progeny influences replenishment of marine populations. 'Sources' are considered as areas that contribute disproportionately large quantities of recruits to future generations while 'sinks' receive recruits but contribute little as spawning areas for subsequent recruits (Pulliam 1988, 1996, Roberts 1998).

With respect to *Pinctada maxima* fishery in the 80 Mile Beach area, Western Australia, there has been a longstanding hypothesis within the industry that 'source' populations in deeper areas (e.g. Compass Rose, offshore stock – see Section 4.7) are a contributing factor to the continued recruitment to the 'sink' area, i.e. the shallow water pearl grounds. These grounds are the focus of the pearl fishery and anecdotal evidence reports a paucity of MOP shell in these areas. The depth and location of these source populations impose physical constraints on harvesting by divers and they are only lightly exploited. Consequently, any future harvesting of MOP oysters from these hypothesised source areas must take into consideration the effect on the viability of the lucrative shallow water stocks.

The objectives of this section are to review theoretical and empirical evidence on source-sink connectivity in invertebrate marine populations, summarise the evidence on connectivity of pearl oyster stocks, and assess the effect of this on any harvesting of MOP. Existing 'source-sink' literature, and data on pearl stock abundance and distribution were reviewed. Data on stock abundances came from historical catches, a 25-year (1978-2002) daily catch and effort database, and a large-scale stock survey undertaken during this project (Section 4.7).

Future research to further examine the source-sink hypothesis in the *P. maxima* stocks is discussed.

3.7 Protocol for management of MOP stocks

3.7.1 Assessment of MOP stock abundance

Outcomes of growth, fecundity, mortality, historical catches, stock distribution and abundance, and review of stock and recruitment relationships were used to develop an appropriate protocol for any future harvesting of MOP populations.

To facilitate discussion, we calculated standing stock of MOP shell (N_{MOP}) based on estimates of the number of pearl "patches" or "reefs" and the total area of each reef. These estimates were obtained from historical and current data, and interviews with skippers with many years experience in the fishery. Note that the number of reefs known, and the spatial area of each reef are also estimates, rather than exact measurements.

$$N_{MOP} = \sum_{i=1}^{P} \sum_{j=1}^{H} \frac{h_j}{q_j} \frac{A_{ij}}{S} \tag{6}$$

where N_{MOP} is the estimate of standing stock (number of oysters) of MOP,

P is the total number of pearl oyster "patches" or reefs,

H is the total number of habitats within a patch [1..3; 1 = inshore (9-12m), 2 = midshore (13-15m), 3 = offshore (15-20m)],

A_{ij} is the area of habitat j in patch i. Habitat j was assumed to be 100% (if depth of the patch was narrowly restricted to one habitat), 50% (if the patch encompassed two habitats), or 33.3% (if the patch encompassed three habitats) of the total area of patch *i*. These are only estimates and will be improved by quantitative habitat data currently being collected as part of FRDC project 2000/127 (FRDC, 2000). Total area of currently fished pearl reefs (not including Compass Rose) estimated at 225 km^2.

h_j is the mean catch rate of MOP (number caught per diver hour) in habitat *j*

q_j is the catchability of MOP oysters in habitat *j* (Table 2).

S is the area swept (0.01408 km^2 per diver hour – estimated with data from Joll, 1996)

Two estimates of N_{MOP} are made: 1) a minimum estimate, based on currently fished (since 1985) areas and the areas encompassed by the stock survey. This is conservative and will be an underestimate; 2) a maximum estimate – which takes into account historically fished areas and assumes that 30% of the stock (see section 4.4.2 for justification of this assumption), is not currently fished and exhibits a population size structure and density equivalent to that found in the very lightly fished deepwater stocks (Compass Rose).

3.7.2 Harvest estimates of MOP

Usually, a reduction in virgin biomass via harvesting can bring about increased recruitment through release of density-dependent competition. However, our initial approach to gaining harvest estimates of MOP is a conservative one, and based on maintaining current stock levels. Therefore, a proposal for MOP harvest under this regime requires that recruitment into the MOP population be greater than natural mortality, and thus any harvest would be "creaming" off the excess productivity. The balance of these demographic processes on 80 Mile Beach *P. maxima* stocks was examined under the following equation.

$$N_{MOP,\,t+1} = G_t + e^{-M} N_{MOP,\,t} \tag{7}$$

where $N_{MOP,\,t}$ is number of MOP in year *t*;

G_t is the number of animals growing (recruiting) into the MOP population at time *t*. G_t is usually expressed as a transition matrix (**G**), in which G_{ij} are the probabilities that an oyster in size class *i*, will grow into size class *j* (Haddon, 2001). Under this equation, a range of estimates of recruitment into MOP will be obtained depending on assumptions and variability in growth, natural mortality, and spatial distribution of catch rates. We assume all *P. maxima* in size class *i* grow into size class *j* (MOP), and examine growth for 3 size classes of *i*, corresponding to good (9mm $year^{-1}$), average (7 mm $year^{-1}$) and poor (5 mm $year^{-1}$), recruitment. Data on growth are obtained from Figure 8. Such an approach is sufficient for the purposes of exploring the notion of MOP harvest, but not for a formal population dynamics model.

Equation 6 can be used to estimate h_j, which is the catch rate in a good (166-174mm shell), average (168-174mm shell), and poor (170-174 mm shell) recruitment year. Estimates of h_j obtained from the stock surveys (Section 4.7).

M is the natural mortality rate – a range of values of M (0.02 to 0.2) was examined. These reflected the estimates derived in section 4.2.

Table 2. Habitat characteristics in the *Pinctada maxima* fishery and their relationship to depth and MOP shell catchability. Assumptions regarding habitat composition are made so that MOP shell catchability (*q*) estimates from Joll (1996) can applied to CPUE data from the stock surveys. *q* is expressed here as the proportion (or %) of oysters present in the area searched by pearl divers, that are caught. These catchability estimates can also vary depending on visibility.

Depth (m)	Habitat Type	Habitat Composition.	Catchability (*q*)
9-12	Inshore	"Potato/Asparagus" – 100%	0.16 (16%)
13-16	Midshore	"Potato (50%)/Garden (50%)	0.26 (26%)
16-20	Offshore	"Garden" – 100%	0.37 (37%)
30-34	Unfished Deep	"Garden" – 100%	0.37 (37%)

General fouling on pearl shell

B grade (little or no cliona)

FAQ grade (llevel i and ii cliona)

C grade (level ii cliona)

Figure 7. Pictorial identification of *Cliona* infection grade categories.

4.0 Results and Discussion

4.1 Growth

Data on overall growth of pearl oysters is summarised in Table 3 and Figure 8. Growth at Exmouth Gulf and 80 Mile Beach is similar, while growth at Lacepedes is slightly faster (higher K), and the L infinity slightly higher (207). Annual growth increment (in mm of DVM) from the different regions varies from 8mm per year (160mm DVM) to 3 mm per year for large MOP (220mm+ DVM; Figure 8).

Table 3. A summary of estimated parameters of the Von Bertalanffy growth curve for *Pinctada maxima* from the northern (Lacepede Channel), middle (80 Mile Beach), and southern (Exmouth Gulf) sections of the pearling grounds.

Location	L_∞ (mm)	K
Lacepede Channel	207	0.31
80 Mile Beach	204	0.24
Exmouth Gulf	204	0.27

Growth of Mother of Pearl (175mm+)

Generation of ages from an age-length key showed that oysters in the MOP size-range (175mm+ DVM) for 80 Mile Beach were aged between 7 and 19 years of age (Table 4). Age-length key based on t = 0 so ages are relative. Growth in length of MOP slowed considerably with increasing age. In the 9th year the increase in DVM was calculated at 6.3 mm per year, with growth falling by 1.4 mm yr^{-1} in the following year (to 4.9 mm yr^{-1}) and to 3.9mm in the 11th year. The average growth rate from 10 –15 years was 2.9 mm yr^{-1} .

At the Lacepedes Islands, oysters reached MOP size classes at 6-8 years (Table 5). The age-length key shows that oysters were predicted to grow to 200+ mm when they reached 8-17 years. Growth in DVM of MOP at the Lacepedes Channel, is calculated as 6.3 mm yr^{-1} in the seventh year. This growth in DVM falls by 2.2 mm yr^{-1} in the 8th year (to 5.9 mm yr^{-1}) and to 4.3 mm in the 9th year. The average increase in DVM from 10 –15 years averaged 1.6 mm yr^{-1}.

Growth in length (DVM) of MOP at Exmouth Gulf, which begins at 6 y 4 m, is calculated as 8.6 mm yr^{-1} in the seventh year. This growth in DVM falls by 2.3 mm yr^{-1} in the 8th year (to 6.4 mm yr^{-1}) and to 4.7 mm in the 9th year. The average increase in DVM from 10 –15 years averaged 1.8 mm yr^{-1} .

Annualised growth of shell from Exmouth Gulf (1998 – 2000) from mortality experiments for oysters over 175 mm DVM (subsample of 104 measures) was similar or slightly higher than recorded in previous research (Figure 8).

Table 4. Age length key built from mark recaptures – proportions. All oysters from shallow water 80 Mile Beach.

Linf = 203.9872	K = 0.242975	T = 0

	Age (yrs)							**MOP Shell**										
Length (cm)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
3	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0.92	0.08	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0.70	0.30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0.05	0.95	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0.91	0.09	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0.63	0.36	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0.20	0.78	0.02	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0.03	0.86	0.11	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0.24	0.75	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0.01	0.83	0.16	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0.19	0.77	0.04	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0.01	0.50	0.43	0.06	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0.05	0.58	0.33	0.03	0.01	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0.05	0.51	0.35	0.09	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0.09	0.22	0.35	0.35	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0.12	0.35	0.15	0.23	0.08	0.04	0	0	0	0.04
20	0	0	0	0	0	0	0	0	0	0	0	0.43	0.00	0.14	0.14	0.14	0.14	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.00	0
Total n	18	440	1287	1598	1038	695	686	483	503	593	104	335	52	86	60	60	286	26

Table 5. Age length key built from mark recaptures – proportions. All oysters from Lacepede Channel and Hama Patch. Note: L inf and K are different in value to parameters calculated in the growth chapter. These figures were calculated through the process introduced in Haddon (2001).

Linf: 206.4374	K: 0.3080	To: 0

	Age (yrs)						MOP shell									
Length (cm)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**16**	**17**
4	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	1.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0.67	0.33	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0.29	0.71	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0.09	0.91	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0.01	0.89	0.09	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0.65	0.32	0.03	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	1.00	0.00	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	1.00	0.00	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0.50	0.50	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0.50	0.50	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	1.00	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0.44	0.48	0.08	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0.36	0.40	0.21	0.03	0.00	0	0	0	0	0	0
19	0	0	0	0	0	0	0.29	0.38	0.18	0.08	0.02	0	0.03	0.02	0	0
20	0	0	0	0	0	0	0	0.03	0.48	0.18	0.06	0.12	0.06	0.06	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0	0.50	0.50
Total	12	108	397	133	153	93	86	71	85	31	9	15	11	9	65	65

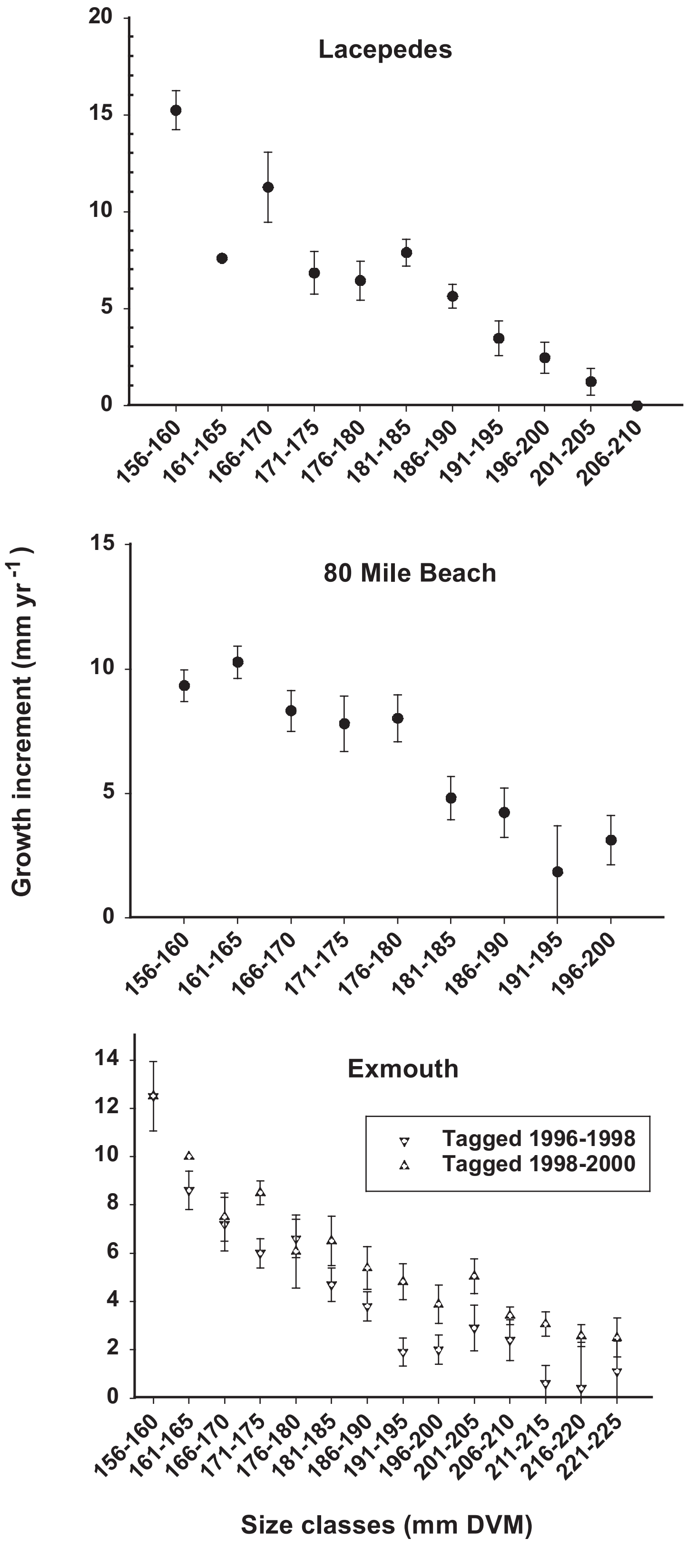


Figure 8. Annualised growth increment in DVM of MOP sized *P maxima* from Lacepedes, 80 Mile Beach and Exmouth.

4.2 Mortality

4.2.1 Effect of handling on mortality and tag retention.

Of the 93 shell originally placed on line 1 in Exmouth Gulf in July 1998, 92 were found in August 1998 and examined *in situ*. From these 92 shell, 2 were dead, 3 had damaged tags and 1 shell had lost both tags. Therefore, total mortality from experimental handling was 2/92 = 2.17%.

4.2.2 Mortality estimates from tagging

From the 200 oysters placed-out for 1 year in August 1999, 195 were retrieved live in August 200, 2 were dead and three were not relocated. The collection rate of 195/200 (97.5%) indicates that mortality was low (2.5 % p.a.).

Mortality of "dumped" shell (from the 8 piles of 10 shell simulating a dump scenario) was 0 - 100 % survival. Thus, overall direct estimates of annual natural mortality of MOP shell were 1 - 2%, which equates to an M of 0.02.

4.2.3 Catch curve analysis of mortality (80 Mile Beach)

Natural mortality (M) ranged from 0.18 or 16.5% per year (80 Mile Beach, inshore shallow) to 0.1 (9.5 %) at the Compass Rose deepwater stocks (Figure 9). Mortality at the Lacepede Islands (0.148) and 80 Mile Beach offshore shallow was intermediate between these. This trend is correlated with depth, i.e. highest mortality in shallower waters and lowest in deep.

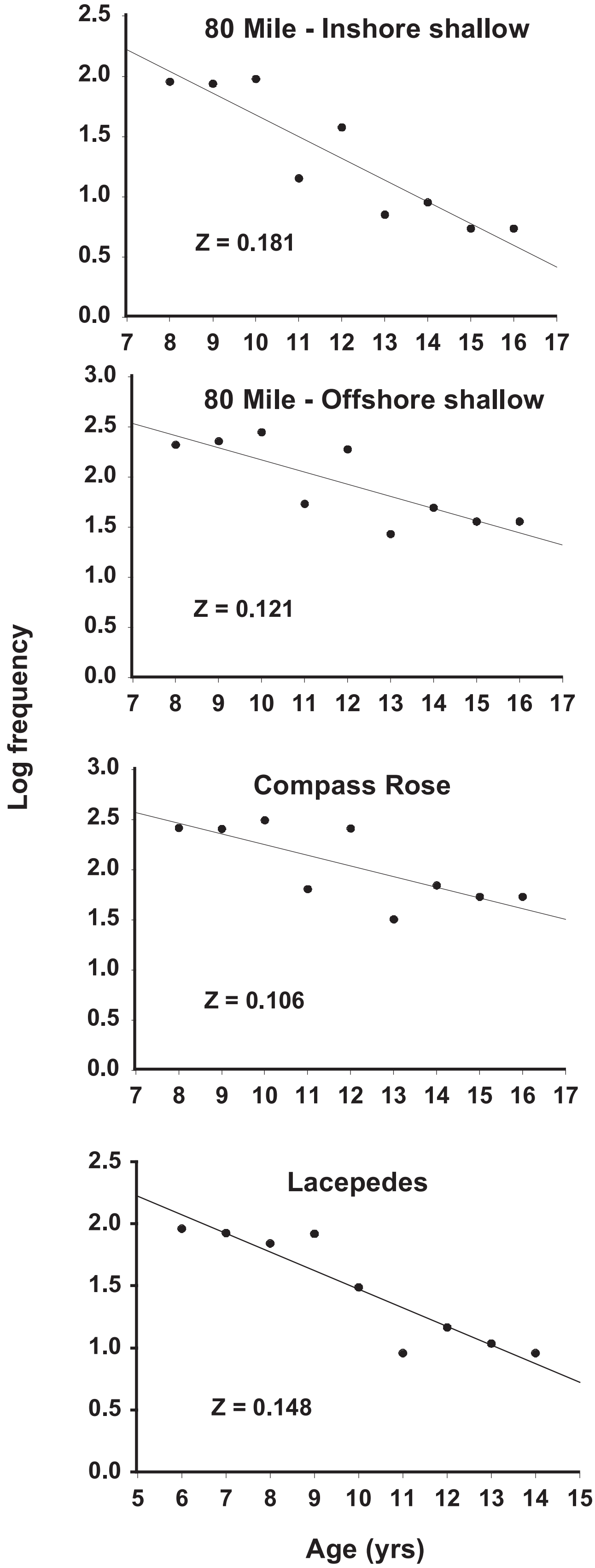


Figure 9. Length-converted catch curve for oysters sampled at 80 Mile Beach, Compass Rose and Lacepedes. Growth in the 80 Mile beach regions and Compass Rose is assumed to be equal when generating these data. Z = total mortality = M = natural mortality.

4.3 Sex Ratios, Gonad Development and Size - Fecundity

Sex-ratio confirms that *Pinctada maxima* are protandrous hemaphrodites (Figure 10). Size at-maturity for males was around 110 mm, females were identified from 135 mm onwards and the sex ratio reached 50:50 female to male at approximately 170mm DVM. From 170-200mm there was a greater proportion of females in the population.

There was a significant correlation ($R^2 = 0.96$) between mean gonad dry weight and gonad stage for the oysters sampled in Exmouth Gulf in January 1998 (Figure 11).

For shell collected at Exmouth Gulf, there was no significant difference in gonad weight between four (17-19cm; 19-21; 21-23; 23-25 cm) size categories ($F(3,38) = 0.44$).

There was no significant correlation between size of the oyster and gonad dry weight within stage 4 (gravid) individuals from Exmouth Gulf (n = 13; $R^2 = 0.004$; Figure 11). There was also no significant correlation between size of the oyster and gonad volume within stage 4 (n=10; r = 0.36; $p>0.05$) from Hancocks (1993) fixed samples from 80 Mile Beach.

In the fixed samples, gonad was, on average, 23.4 % of the visceral sections examined (range = 18 % - 29 %). The average gonad volume of the 10 “late developing” individuals (180 and 220 mm DVM) was 5031 mm^3 (range = 2963 - 6329 mm^3), with an average total oocyte volume of 2012 mm^3 (range = 1185 – 2531 mm^3).

No significant correlation was found between fecundity (no of eggs) and shell length of *Pinctada maxima* for either fixed or dried gonad samples.

A comparison of estimates of fecundity (Stage 4 females only) obtained from 2 methods (dried samples vs fixed samples) yielded significantly different estimates of total fecundity. The mean number of eggs in fixed gonads from 80 Mile Beach, obtained during Hancock’s (1993) study was $39.4 \times 10^6 \pm 9.2 \times 10^6$ SD (Figure 12). In comparison, the mean number of eggs found in dried gonads from Exmouth Gulf was $24.6 \times 10^6 \pm 4.9 \times 10^6$ SD.

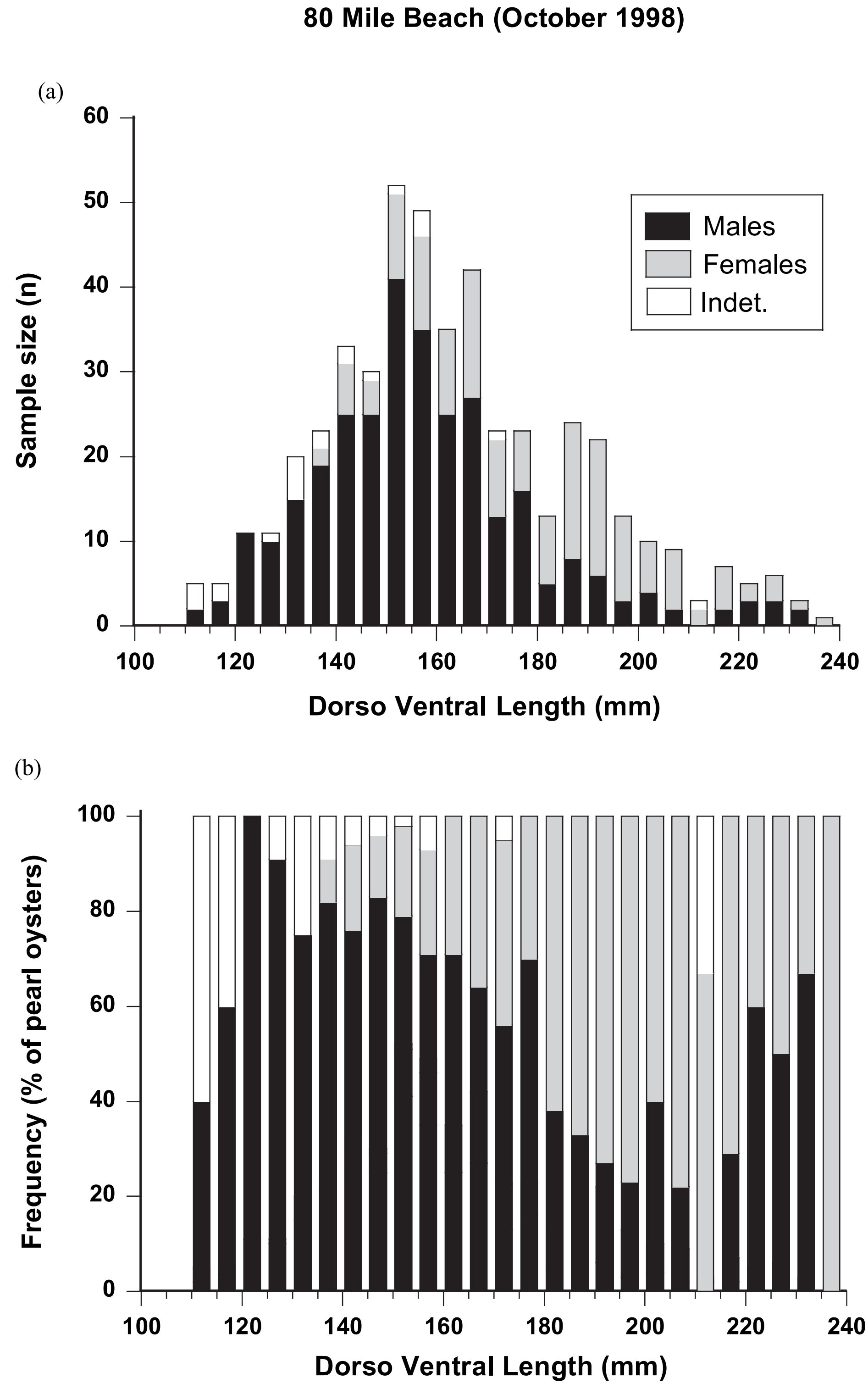
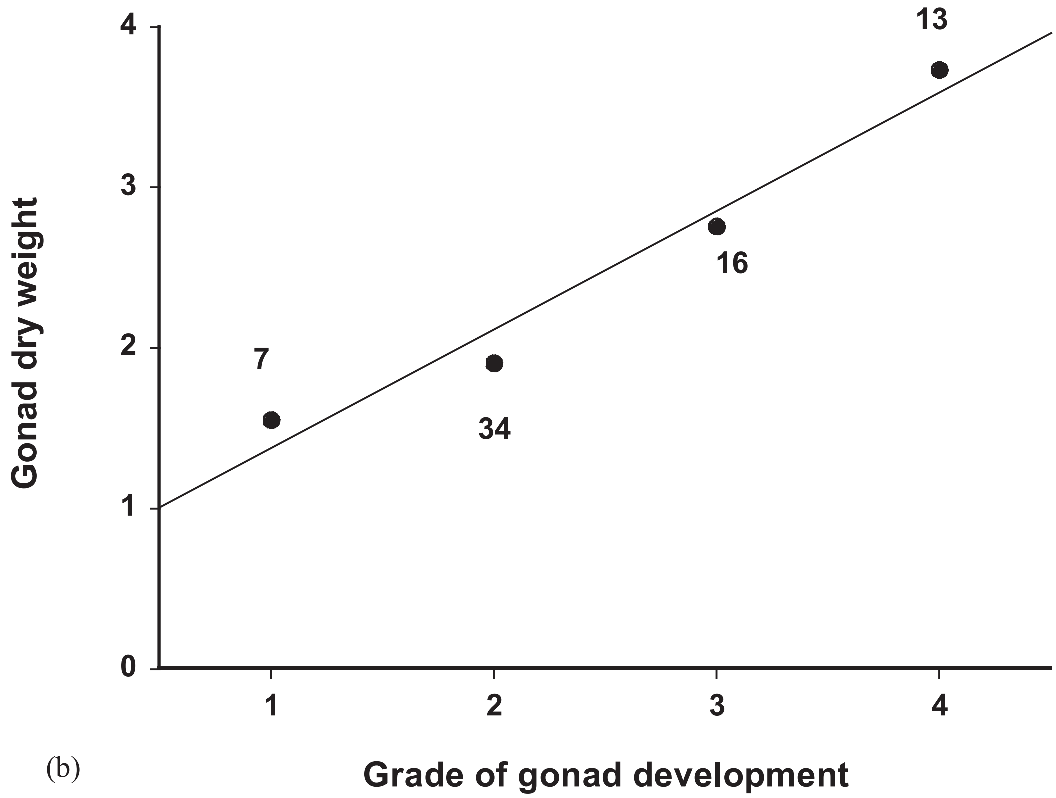


Figure 10. Sample size (a) and sex ratios (b) of pearl oysters from 80 Mile Beach (sampled October 1998).

(a)



(b)

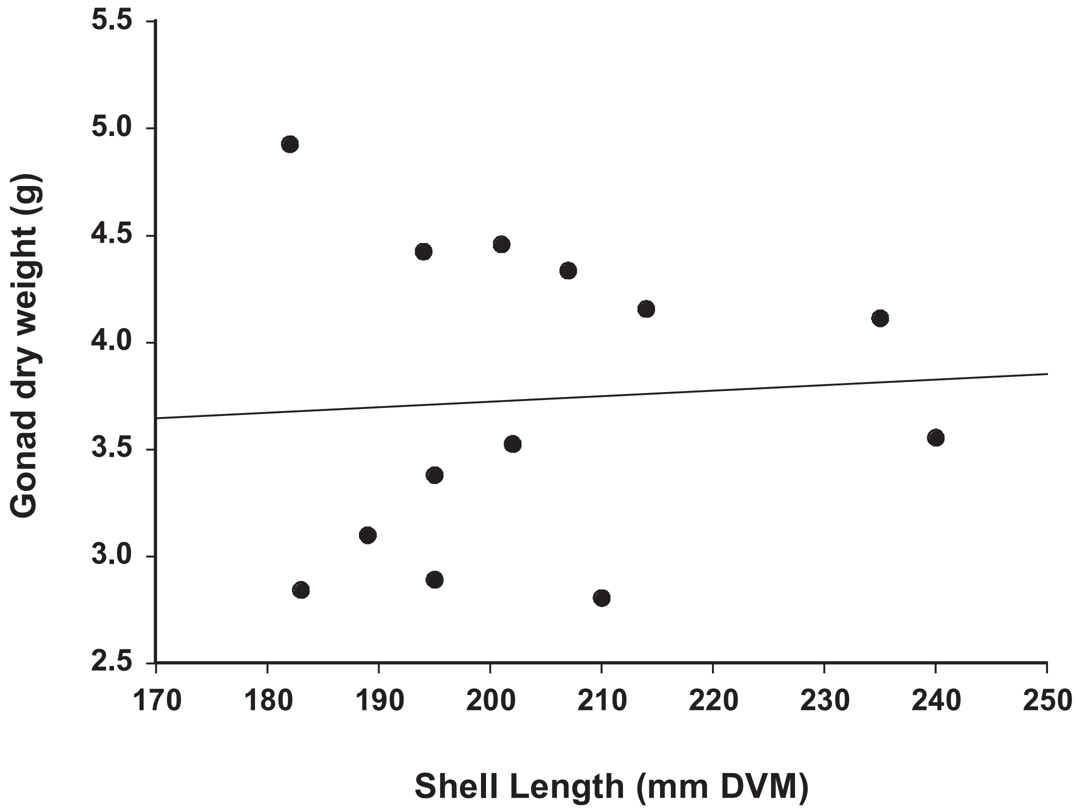


Figure 11. (a) Gonad weight as a function of gonad development stage in *Pinctata maxima.* Numbers refer to sample size. (b) Dried Gonad weight for stage 4 gonads as a function of shell length. Data from Exmouth Gulf, January 1999.

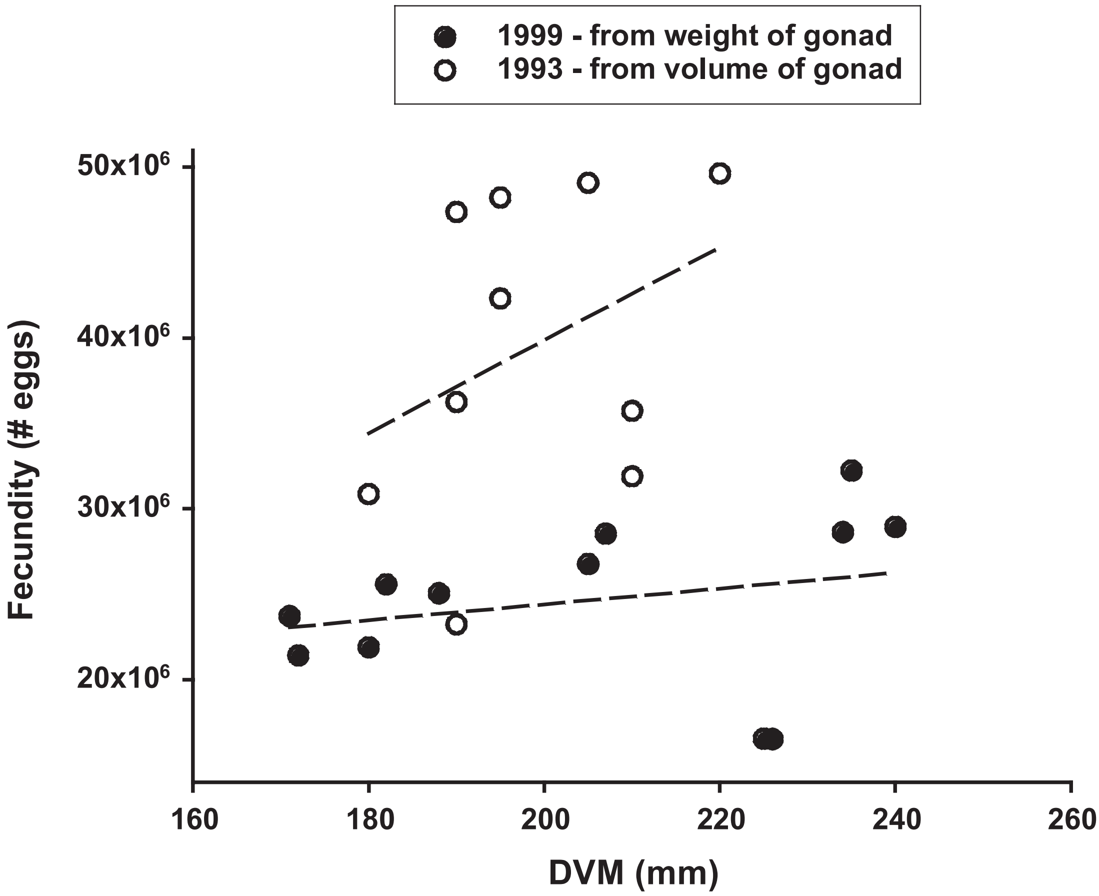


Figure 12. Fecundity estimates as a function of shell size (DVM) in mm for two different methods. Weight of gonad (1999 samples from Exmouth Gulf), and volume of gonad (1993 samples from Hancock, 1993).

4.4 Historical Patterns in MOP Catches

4.4.1 1880s – 1970s

The commercial collection of pearl shell developed in Australia by the late 1860's. The early fleet was dominated by Japanese vessels operating in international waters and by Australian pearling enterprises using indentured labour (primarily from Japan). The majority of Japanese controlled fishing was conducted in what are now Northern Territory waters.

Throughout its long history, industry operators have been noted for their independence and this has impacted on the marketing style which has been described as 'price taking'. In as much the value of pearl shell has closely related to prevailing economic conditions, strong depressions in price can be linked with market depressions (eg. 1921, 1958). In the early days (up to 1907), the bulk of Australian pearl shell was exported to the United Kingdom. This market position was supplanted by the USA after the 1st World War and by the late 1950's West Germany became the main market for pearl shell outside of Japan. Japanese pearlers operated off the Australian coast up until 1941 and resumed offshore fishing in the Arafura Sea in 1953. Major peaks in price occurred in 1913, 1919-20, 1930 (£194 per ton) and 1946-47, however the price per ton for MOP fell as low as £87 per ton in 1938/39 (Japanese fleet increase). Following the war and with the introduction of plastics the industry was somewhat depressed, however, an average price reported for the 1950's stood at £552 per ton.

Anecdotal and documentary evidence of activities of pearl luggers and hard hat divers indicates that 17 significant deep water pearling grounds between Champagny Islands (15^0 19' S, 124^0 13' E) and the Montebelo Island (20^0 26' S, 115^0 31' E) were fished. Throughout its history (Coombs 1946, Bain 1982) the pearling industry has collected and sold nacre from mature oysters, which was primarily used for the manufacture of buttons. The large number of MOP caught and engaged in MOP shell collection between 1901 and 1961 gives an indication of the scale of the industry in Western Australia (Table 6, Figure 13). Powered vessels predominated by the 1930's and mechanical pumping of air to divers allowed two divers to work per vessel (Brownfield 1953). Japanese vessels were reported to service up to 6 divers. This increased efficiency of vessels changed the industry dramatically from the 1930's onwards (Table 6). Whereas in 1912 a total of 328 boats averaged 3.9 tons per boat in Western Australia, 24 years later, 51 boats operated with an increased catch rate averaging 11 tons per boat (Table 6).

Official production statistics for broadly described catch areas have been recorded for the Western Australian pearling industry since the 1890's. While MOP collection took place along the entire Kimberley / Pilbara coastline, the 80 Mile Beach area south of Broome provided by far the greater proportion of MOP collected during the history of the fishery (Figure 13). From 1900 to the early 1950's weights of MOP fished were recorded by regional centre (Broome, Cossack and Onslow), however this catch data (by location) could only be found as a series of 'snapshots', rather than a definitive time series (Figure 13c,d). During the 1950's, as part of the Pearl Fisheries Act of 1952-3, broad sub-areas were introduced across northern Australia, which separated the productive Onslow/Cossack, 80 Mile Beach and Broome to Cape Leveque regions, and resulted in better spatial data (Figure 13d).

Table 6. Annual figures on manpower, price and productivity from the MOP Pearling industry for Western Australia (Fisheries Division DPI Canberra 1962).

		MOP		
Date	Men Employed	Average Price	Average production	Value per boat
		(£ per long ton)	(tons per boat)	(£)
1901	1555	114.9	3.59	412
1902	1756	147	3.63	534
1903	2317	129.1	2.96	382
1904	2700	96.3	3.32	320
1905	2228	103.7	3.58	371
1906	2455	106.8	3.39	359
1907	2500	121.9	3.64	443
1908	2304	125.2	3.69	463
1909	2267	158.6	3.61	573
1910	2513	168.3	3.43	577
1911	2519	191.1	3.30	631
1912	2718	264.2	3.98	1051
1913	2743	161.7	3.93	635
1914	2644	151.1	4.06	613
1915	1567	115.7	4.71	545
1916	2133	149.7		
1917	2349	118.8	6.33	752
1918	1745	126.6	5.55	703
1919	2080	182.9	5.01	916
1920	2504	161.3	4.88	787
1921	1594	132	5.68	750
1922	1571	135.1	5.94	802
1923	1701	128.1	6.15	788
1924	1599	158.6	6.66	1056
1925	1746	149.2	5.73	854
1926	1470	152.7	5.32	813
1927	1013	157.8	6.11	963
1928	946	160.9	6.59	1061
1929	902	169.5	7.18	1216
1930	777	155.4	5.28	821
1931	836	160.2	4.67	748
1932	779	133.2	6.01	800
1933	774	106.8	6.50	694
1934	702	106.1	7.21	766
1935	529	104.9	4.99	523
1936	614	124.6	9.17	1142
1937	633	136.5	11.21	1530
1938	652	89.1	12.85	1144
1939	565	87.2	11.05	964
1940	536	105.6	10.77	1137
1941-1945	WWII			
1946	133	567	6.5	3684
1947	267	614	11.03	6771
1948	251	500	11.59	5800
1949	234	350	13.56	4745
1950	222	467	13.54	6326
1951	209	543	16.05	8722
1952	190	586	18.88	11055
1953	269	634	17.23	10916
1954	313	638	20.63	13169
1955	379	636	18.63	11847
1956	467	653	21.80	14234
1957	484	606	23.14	14015

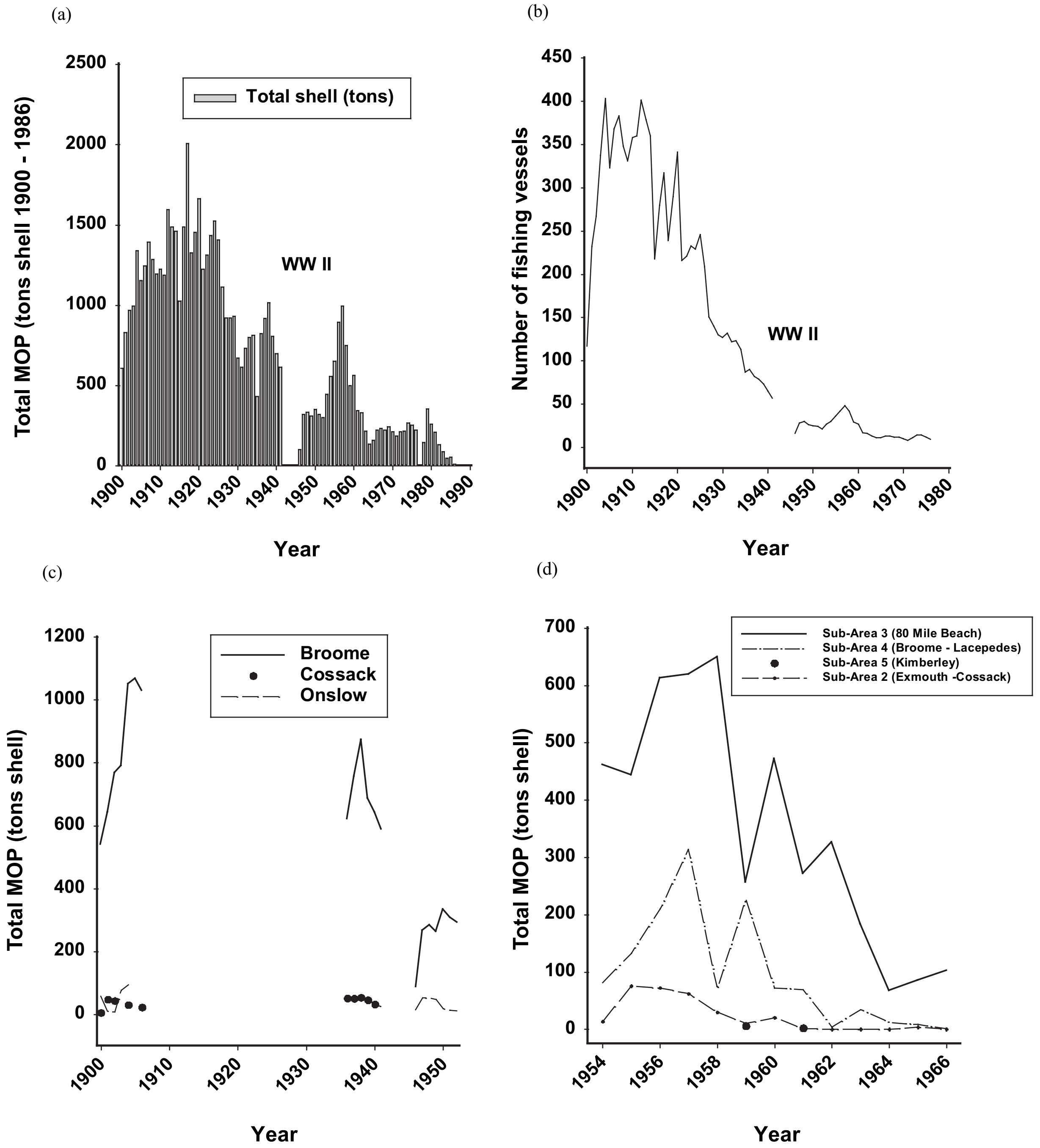


Figure 13. (a) Historical catch of MOP (b) effort (vessel numbers) from Western Australia 1900 – 1980 and MOP landings as recorded by (c) port and (d) sub-area.

Between 1900 and 1954, MOP landings at the port of Broome peaked at a reported 1067 tons per annum (Figure 13c) (note 1 ton = 1016 kg). This equates to a take of between approximately 897,00 and 1,128,000 pearl oysters per year (average MOP shell weight of 961 g - 1128 g). The average reported catch for Broome port was 595 ton a year, or between approximately 500,000 and 639,000 oysters per year (Figure 13). This catch far outweighed landings reported from more southerly ports where an average of 63 tons was fished annually (reported years). Between 1954 and 1966, MOP landings from the 80 Mile pearling grounds, Lacepedes, Kimberley and sub areas further south declined to less than 150 tonnes (Figure 13a).

With the increasing focus on the collection of smaller culture sized shells and the introduction of daily catch logbooks, more precise data on the total number of shell caught, shell type and catch areas was recorded from 1978 onwards.

4.4.2 1978-1986.

During the early 1980's concerns were raised regarding the importance of MOP shell as a probable broodstock source for recruiting shell on the shallow 80 Mile Beach grounds (which provide the more lucrative culture shell component of the fishery). As a result the taking of MOP was prohibited from 80 Mile Beach (Zone 2) from 1985, and from Exmouth to Port Hedland (Zone 1) from 1984. MOP fishing continued on a limited scale to the north of Broome until 1986.

Total number of MOP shell caught in Zone 2 (South of Broome) and Zone 3 (North of Broome) areas of the fishery decreased from 356,000 in 1979, to 11,000 in 1986 (Table 7). This was the last year in which MOP were commercially caught.

Table 7. Historical changes in pearl shell catch and effort from 1978 till 1987 in Zone 2 (South of Broome) and Zone 3 (North of Broome) of the pearl fishery. (from State of the Fisheries, 94/95)

Year	No. of culture shells	No. of MOP shells	Total Shells	Culture Shells/hr
1978	404 952	146 692	551 644	38.26
1979	371 806	355 599	727 405	23.14
1980	364 502	260 714	625 216	19.63
1981	481 193	210 649	691 842	20.63
1982	439 092	132 931	572 023	27.95
1983	365 381	87 049	452 430	19.21
1984	242 828	47 230	290 058	20.9
1985	272 869	53 831	326 700	21.96
1986	337 566	10 929	348 495	20.48
1987	365 397	0	365 397	20.9

Between 1978 and 1986, there were 25 blocks where 5000 + MOP shell were harvested (Table 8). The majority of these blocks were in the 80 Mile Beach-Compass Rose-Wallal area and recorded (81%) of the catch in number of shells taken. Recorded catch rates for MOP in 10 x 10 mile blocks for both time periods reached 85.7 MOP shell/hr per grid yr^{-1} with an average of approximately 20 shells/hr (Table 8). Of the grids historically fished for MOP, 36% (9/25) are not currently fished, i.e. did not have more than 5000 shell taken from them in the period 1995-1996 (Table 8; Figure 14). In terms of number of oysters, 128,000 MOP (19%) were fished from grids that are no longer fished, compared to 534,000 (81%).

These figures were used to guide our assumptions on what area of reef is currently not fished, but could produce MOP, so as estimate standing stock. We assumed a figure of 30% of the area of currently fished pearl reefs (see sections 3.7.1 and 4.10.1).

Table 8. **MOP data for 10 x 10 mile grids where >5000 shell were caught between 1978 and 1986. Grid code generated by a combination of latitude and longitude. See Figure 14 a spatial map of grids.**

Grid Code	Catch Total No.of MOP	Av. Catch Rate MOP/Hr	% MOP	Grid currently Fished?*
3060	47585	16.8	47.0	Y
3557	21936	42.2	69.0	N
3657	10481	26.1	69.0	N
3658	12103	35.9	73.0	N
3758	13456	37.2	59.0	N
4152	8543	43.7	52.0	N
4155	10561	9.2	44.0	Y
4156	35224	2.7	1.0	Y
4253	29134	29.9	53.0	Y
4254	55999	33.8	48.0	Y
4255	52631	12.5	30.0	Y
4256	8410	0.7	3.0	Y
4352	8322	27.5	64.0	Y
4353	29995	10.3	45.0	Y
4354	93592	6.7	13.0	Y
4355	25499	2.2	0.5	Y
4453	10753	2.3	7.0	Y
4454	19111	1.4	2.0	Y
4652	70903	24.2	44.0	Y
4749	18107	23.6	74.0	N
4750	29667	Na	69.0	Y
4940	5624	15.7	58.0	N?
5121	29964	35	41.0	N
5233	7555	24.4	45.0	N
5819	6701	23.1	47.0	Y

* Grids currently fished refers to those grids where more than 5000 shell were taken during 1995-1999.

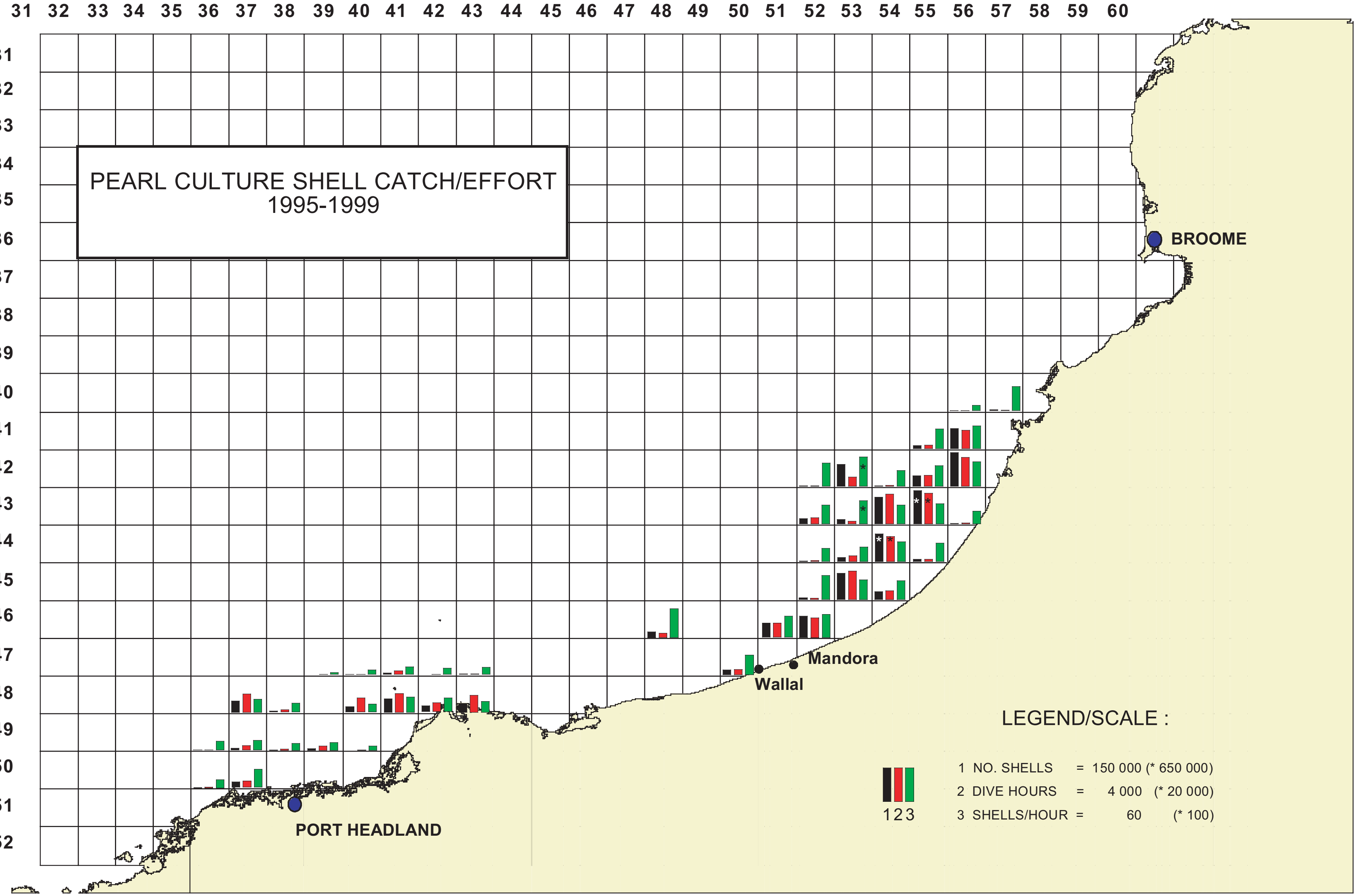


Figure 14. Spatial map of culture shell catch and effort (coded by colour, see legend) from 1995 to 1999. * refers to grids where the data are in excess of the scale provided by the legend.

4.5 Stock Surveys – Pilot Study

4.5.1 Industry sampling of "culture" and "MOP" shell.

Comments on the feasibility of sampling culture and MOP shell during commercial operations were generally negative. All related to difficulties involved in collecting the non-commercial sized shell, when the primary objective was to collect commercial size shell under a strict regime of dive profiles. For example, if MOP were in high abundance, only a proportion of the overall number could be taken due to difficulties in handling the weight. If culture shell were in high abundance, more effort would be directed towards capturing the culture shell, as opposed to unbiased collection of all shell. These difficulties were encountered, even with a $2 per shell incentive to collect MOP shell.

4.5.2 Abundance and stock structure data.

Determination of stock structure and abundance over a drift requires an unbiased collection of all shell detected. Stock structure estimates of MOP stock were obtained for animals larger than 180mm, as were estimates of the size-frequency of 'culture' size animals, bu only unbiased through the 120-150 mm sizes (Figure 15). Due to variations in shell quality and selection, the sizes in the ranger 150- 185 mm DVM were not representatively sampled.

4.5.3 Trials of Alternative Methods / Improvements

There are a few potential alterations to the sampling design of stock surveys which could be made to increase the accuracy of data collected as part of commercial operations. For example:

- One shell collection drift would be nominated each day, with each diver collecting some MOP, and estimating the percentage of MOP shell collected, against the numbers actually seen during the drift.

This method was trialed for one drift. After an all shell pick-up drift, each diver was asked to estimate the percentage of MOP collected by them against that seen by them during the drift. The highest catch of MOP shell was 35 and the lowest 11, with an average of 23. The percentage caught estimates ranged from 30% to 80 %, with an average of 56%. Using this information, MOP abundance was estimated at 255 for the drift. Limitations include variability in individual diver assessments, and no way of 'ground truthing' those assessments.

An alternative method could involve two or three "all shell" collection drifts to obtain stock structure for a patch, combined with a number of randomly selected drifts where MOP shell counts are undertaken by each diver in addition to normal culture shell collection. This again would provide abundance and stock structure data, however is likely to be very difficult if undertaken within the context of a commercial trip.

The most useful method would involve the charter of a vessel for dedicated research surveys of stock structure within known fishing patches. This would have the advantage of divers dedicated to research observations without the 'distraction' of priority culture shell and the ability to spread survey time and resources to maximum efficiency over different fishing patches (see 4.6 and 4.7).

4.5.4 Biofouling and Cliona infestation

The pilot survey established giid data for biofouling type. The primary fouling organisms were coralline algae and sponges, with ascidians, fire coral, and other algae making up the majority of other fouling organisms. Of the 3053 pearl oysters sampled, 45% had indicators of infection by the boring sponge, cliona. Infection was most apparent on larger oysters, with the proportion of oysters with first and second grade levels of infection most commonly found in culture and MOP sized oysters. Laminated pictorial identification charts were prepared to assist in the identification of *Cliona* sp infestation (Figure 7).

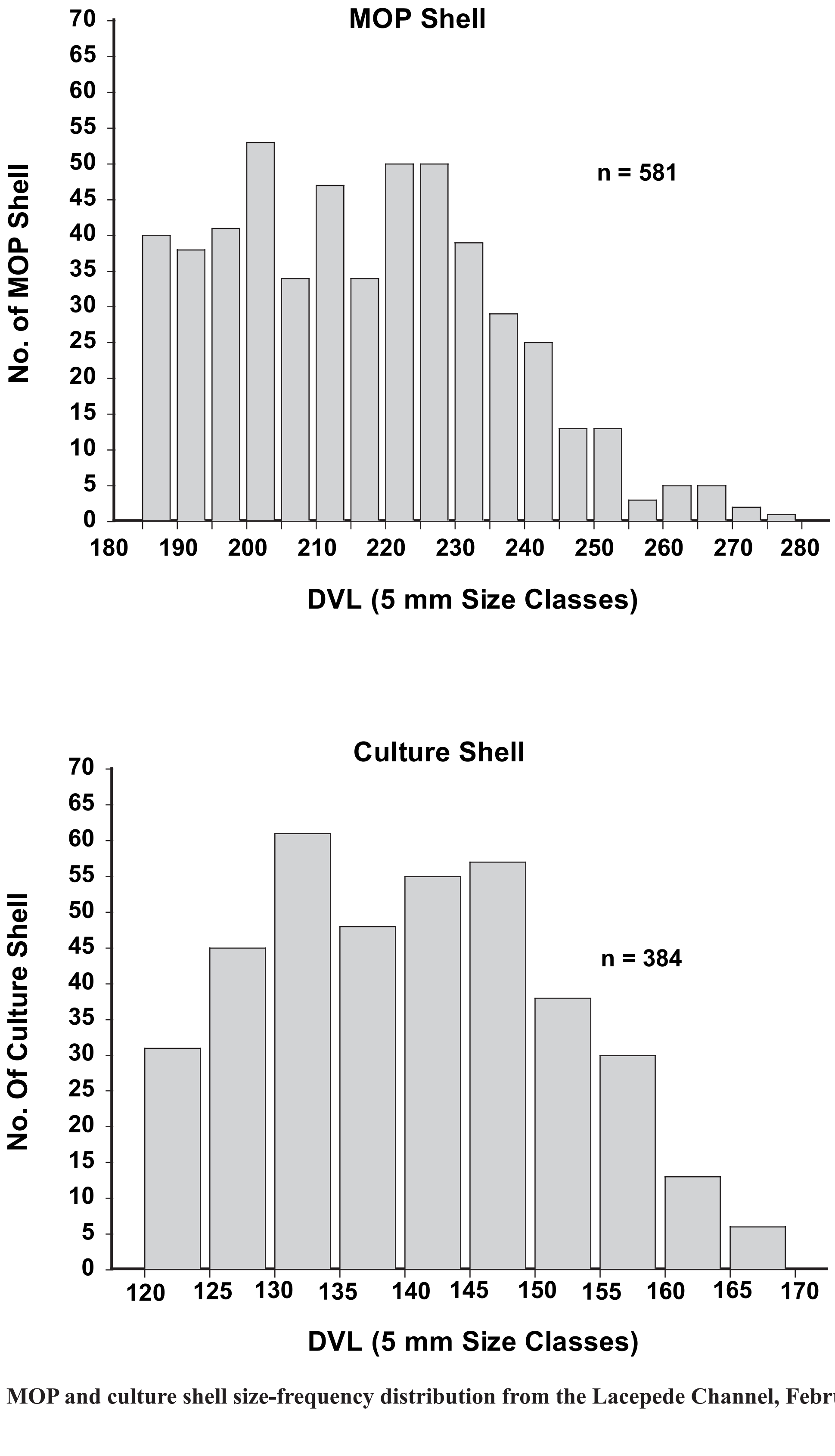


Figure 15. MOP and culture shell size-frequency distribution from the Lacepede Channel, February 1999.

4.6 Stock Surveys - North of Broome

A total of 2356 *Pinctada maxima* were sampled during the stock surveys in November 1999; 2145 from midshore and 211 pearl oysters from deepwater pearling grounds. The majority of the catch (72.3 % - 1703 oysters) came from the currently fished Lacepede channel and Hama patches (Figure 17).

4.6.1 Abundance (Catch per diver hour)

Total Abundance

Mean catch rate at the five midshore pearling grounds was 45 shells per hour. Catch rates varied significantly among locations ($F_{4,64}$= 30.2, $P< 0.001$) and divers ($F_{3,64}$= 12.18, $P< 0.001$). Catch rates were significantly (Tukeys $P< 0.001$) higher at the Lacepede Channel location (73.8 shells/hr) than at the other 4 locations (Figure 16b). Two of the industry divers, Diver 2 (54 shells/hr) and Diver 4 (46 shells/hr), caught significantly more pearl oysters than the other two divers, Diver 1 (30 shells/hr) and Diver 3 (27 shells/hr) at the Lacepede Channel, but not at other locations (Figure 16c).

Undersized shell (<120mm DVM)

Significantly greater catch rates were recorded at the Lacepede Channel (10 shells/hr) and Hama Patch (5 shells/hr) than at the other 5 locations (<2 shells/hr, see Figure 16a), although there was a significant interaction between location and diver ($F_{12,64}$ = 2.13, $P<0.05$). Diver 2 found undersize shell (5 shells/hour) at significantly higher catch rates (Tukey's $P<0.001$) than Diver 1 (2 shells/hour) at the Lacepede Channel only. This spatial trend was similar to that of the culture shell and reflects the regular recruitment received by the 2 sites regularly fished.

Culture shell (120-175mm DVM)

Catch rate of culture shell differed significantly amongst the 5 midshore locations ($F_{4,64}$= 73.2, $P< 0.001$) and divers ($F_{3,64}$= 6.3, $P< 0.001$). A significant interaction ($F_{12,64}$= 4.6, $P< 0.001$) was caused by two of the 4 divers having significantly higher catch rates of culture shell at the Lacepede Channel (averaging over 45 shells/hour compared to <22 shells/hour), but no significant difference between divers at locations holding fewer culture shell with catch rates close to zero (Figure 16a).

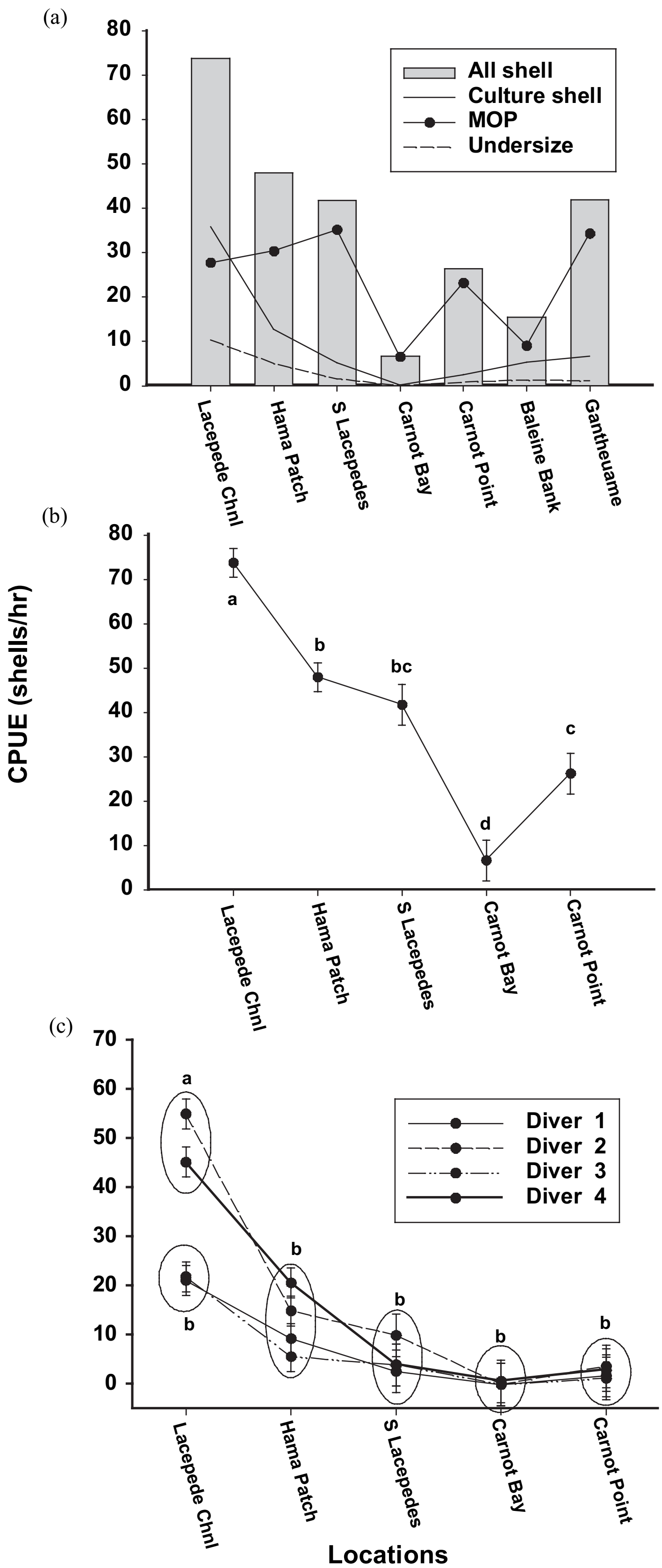


Figure 16. Catch per diver hour of *Pinctada maxima* in November 1999 survey by all locations (a), midshore locations (b), and individual divers (c) for various size categories. Means circled and labelled with the same superscript do not differ in post hoc tests (Tukeys P>0.05).

Mother of Pearl Shell (175mm DVM+)

Both diver ($F_{3,64}$= 5.66, P< 0.005) and location ($F_{4,64}$= 10.56, P< 0.001) had a significant effect on the catch rates of MOP (Figure 16a). These larger shell were taken at significantly (Tukeys HSD, P< 0.01) higher catch rates by Diver 2 (32.5 shells/hr) than Diver 1 (21 shells/hr) and Diver 3 (18 shells/hr). Again there was no significant difference (Tukeys HSD, P= 0.335) between the two more effective divers (Diver 2 and Diver 4, averaging 27 shells/hr). In post hoc tests, catch rates at Carnot Bay (23 shells/hr) were significantly lower (P = 0.01) than at locations close to Lacepede Islands (South Lacepede 35.1 shells/hr, Hama 30 shells/hr, and Lacepede Channel 28 shells/hr). South Lacepeded and Gantheume Point, with low abundance of undersize and culture shell, had good abundance of MOP as a result of the low level of fishing at these locations.

4.6.2 Size structure

Overall

The average length of pearl oysters caught in the midshore pearling grounds was 176.2 mm DVM (±0.96 SE, n=2145) with a range of 19 mm – 296 mm DVM. At the two deepwater locations the average shell length was greater, averaging 203.3 mm DVM (± 2.82 SE, n=211) with a range of 66mm – 273mm DVM (Figure 17).

There were significant differences in mean length of *P. maxima* amongst the 5 midshore locations ($F_{4,2140}$ F=84.71, P<0.001). Oysters from the Lacepede Channel had the smallest mean length (163.2 mm DVM) and were significantly smaller than oysters from the 4 other midshore locations (190.7 mm DVM, n= 1018, see Figure 17). A limited number of oysters were caught at deepwater locations. Oysters collected at the Baleine Banks (185.8 mm DVM, n = 39) were significantly ($F_{1,209}$ = 9.1, P<0.005) smaller than those from Gantheuame (207.3 mm DVM, n=172). This was due to the low abundance of MOP at Baleine Banks.

Undersize (<120mm DVM)

Only small numbers of undersized oysters were taken at most locations and there was no significant difference in the size of undersize shell between the Lacepede Channel and Hama patches, where the bulk of the undersize catch was taken (mean=101.2 mm DVM, n = 218).

In the deepwater locations the small catch limited useful analysis of variation in length among the 3 size class groupings

Culture shell (120-175mm DVM)

The size of oysters within the culture size class range did not differ significantly among the 5 midshore locations fished. Within the deeper locations, culture shell at the Baleine Banks (mean=131.4 mm DVM, n=13) were significantly ($F_{1,39}$ F= 28.5, P<0.001) smaller than those at Gantheuame (154.5 mm DVM, n=28).

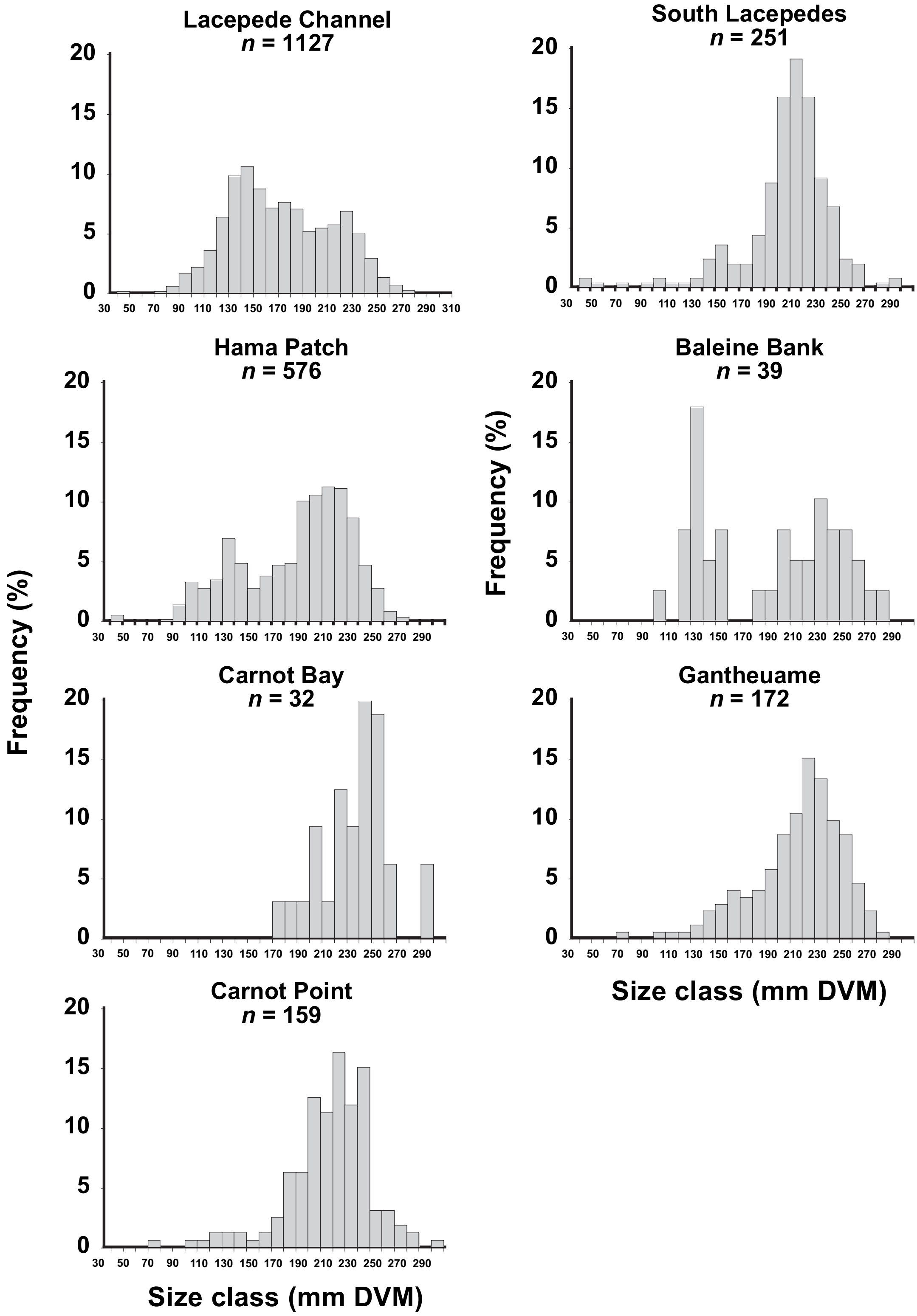


Figure 17. Population size structure (% Frequency) of *Pinctada maxima* at 7 locations north of Broome.

<u>MOP shell (175 mm + DVM)</u>

MOP shell were taken in reasonable quantities at all midshore locations and were largest at Carnot Bay (230.0 mm DVM, n=31) and Carnot Point (218.1 mm DVM, n=138). MOP average sizes were significantly smaller at the three midshore locations in the vicinity of the Lacepede Islands (209.3

mm DVM, n=993). For the deep water stocks, MOP from Baleine Banks (226.7 mm DVM, n=233) and Gantheuame (221.1 mm DVM, n=140) were not significantly ($F_{1,161}$= 1.3, P=0.26) different in length.

4.7 Stock Surveys - 80 Mile Beach

A total of 10803 *Pinctada maxima* were sampled; 8489 from shallow water and 2314 from deepwater pearling grounds at Compass Rose (Figure 18). The overall size structure differed significantly between the shallow and deep pearl grounds (Figure 18).

4.7.1 Abundance (Catch per diver hour)

Divers fishing at locations within the shallow pearling grounds collected a mean of 74 shells per hour (range of 20 - 174 shells/hr). Mean catch rates at the Compass Rose deep water ground was significantly higher at 205.7 shells per hour (Figure 19).

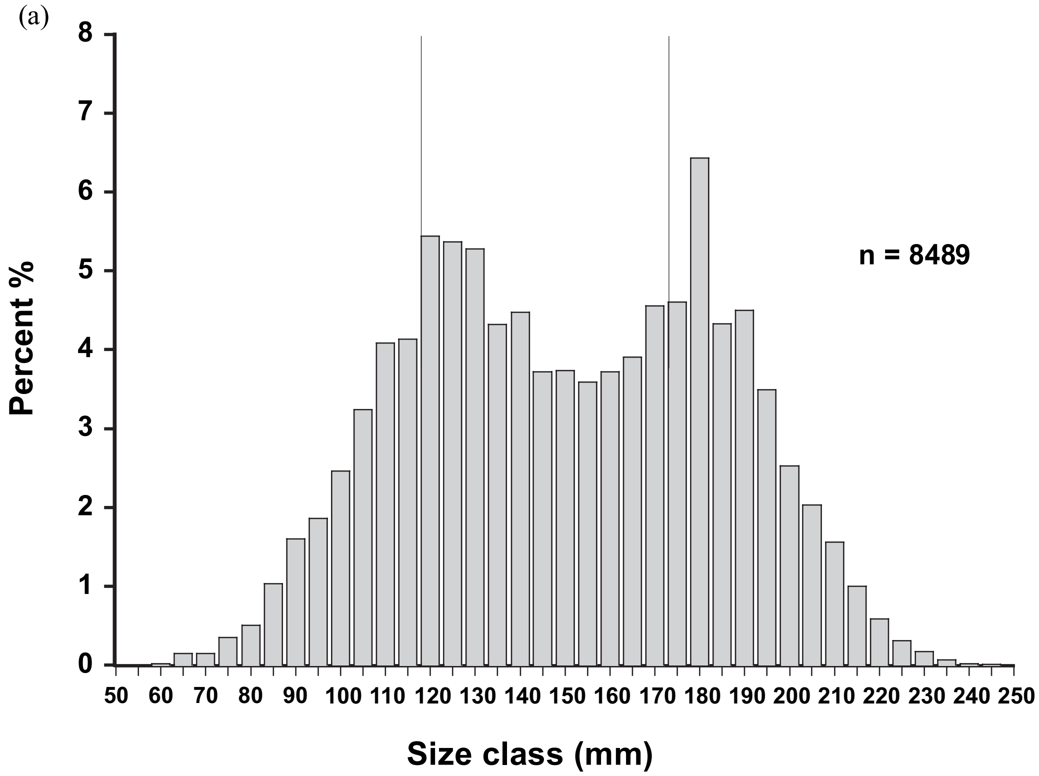
4.7.1.1 Shallow water pearl grounds

Total Abundance

At the 3 locations where inshore, midshore and offshore sites were sampled (5-8 Mile, 10 Mile, 13-15 Mile), there was no significant difference in the catch rate of pearl oysters between divers ($F_{4,89}$= 2.0, P= 0.1). In a comparison of catch rates with divers' catches pooled (location x site), there was a significant interaction ($F_{4,18}$ = 5.17, $P<0.01$) between locations and sites (Figure 19). Catch rates at the 10 Mile offshore survey sites (119.1 shells/hr) were significantly greater (Tukey's $P< 0.05$) than those at 10 Mile inshore sites (61.6 shells/hr; Figure 19).

At the 5-8 mile and 13-15 mile, average catch rates (104 and 71 shells/hr, respectively) were highest inshore. At the 4 locations where inshore and midshore sites were sampled, there were no significant differences in catch rates among locations ($F_{3,16}$= 2.59, P=0.09) or between sites ($F_{1,16}$= 0.13, P=0.72; Figure 19). Catch rates averaged 73.5 shells/hr at inshore sites and 70.5 shells/hr at midshore sites (Figure 19).

(a)



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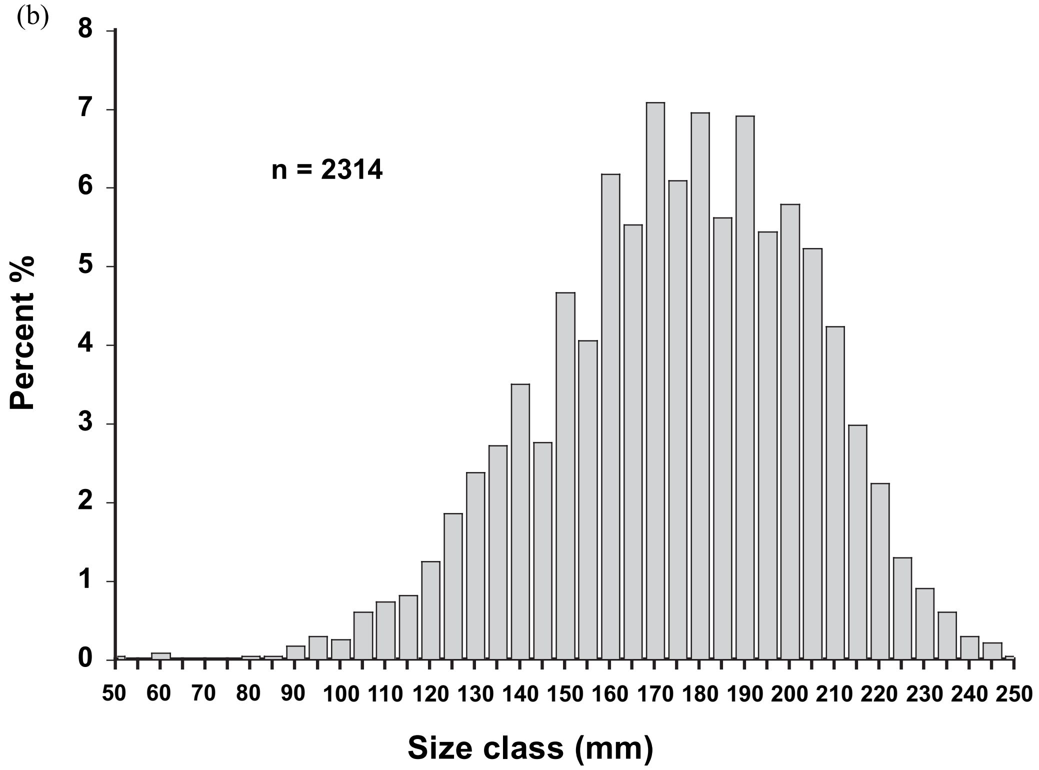


Figure 18. Overall population size structure of *Pinctada maxima* at (a) shallow, and (b) deepwater grounds (The Compass Rose) along 80 Mile Beach.

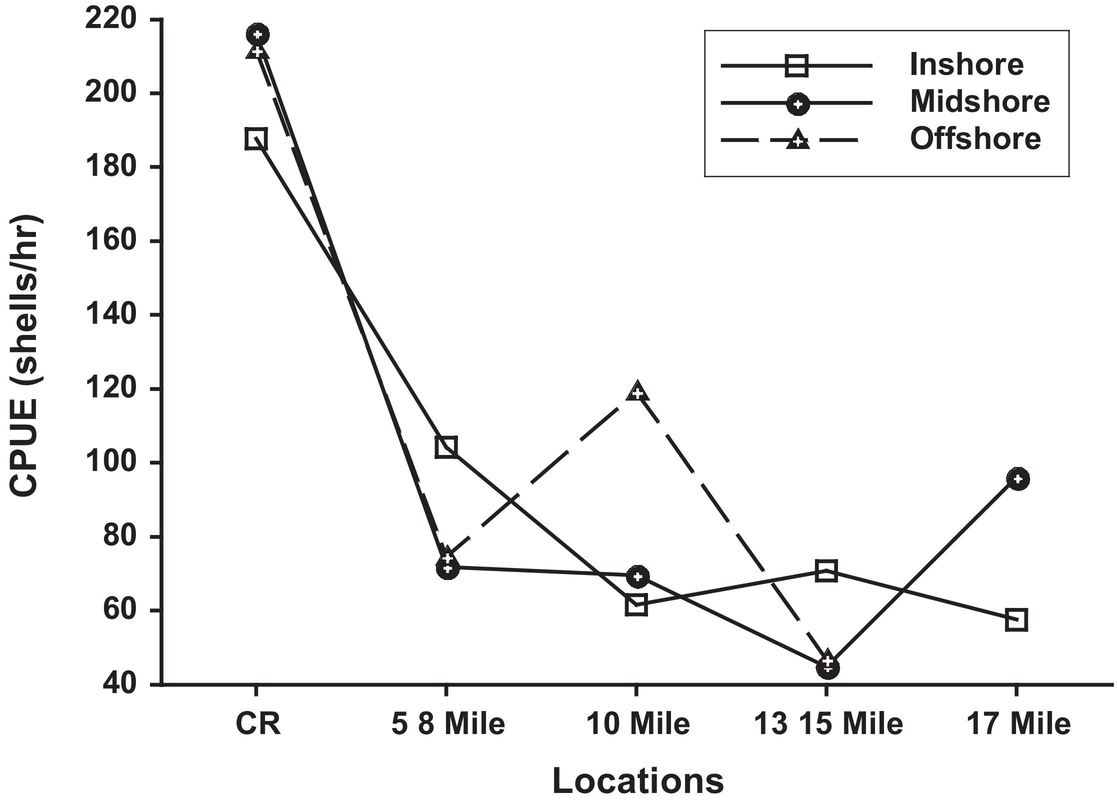


Figure 19. Catch per unit effort for all sizes of *Pinctada maxima* at inshore (9-11 m), midshore (15-17 m) and offshore (17-19 m) sites within shallow (5-8 Mile….17 Mile) and deepwater locations (CR - Compass Rose) along 80 Mile Beach.

Undersized shell (< 120mm DVM)

Undersize shell were found at significantly greater catch rates inshore (34.4 shells/hr) than offshore (2.9 shells/hr) at all locations (Figure 20a). Midshore sites recorded intermediate catch rates (12-15 shells/hr), the exception being the 5-8 Mile where catch rates at midshore sites were similar to those offshore (Tukey's P>0.05; Figure 20a).

Culture shell (120-175mm DVM)

The trend in CPUE for culture shell was similar to the overall CPUE trend (Figure 20b). When individual diver catches of culture shell were pooled, catch rates differed significantly among locations (F2,18,=6.11, P<0.01). Overall, culture shell catch rates were significantly greater at the 10 Mile (43.7 shells/hour) than the 13-15 Mile (25.3 shells/hour), although this difference occurred only at mid-shore and off-shore sites, not at the inshore sites (Figure 20b). Catch rates between the 10 mile and 5-8 Mile (38.9 shells/hour) locations were similar, and no significant difference was detected between the 5-8 Mile and 13-15 Mile.

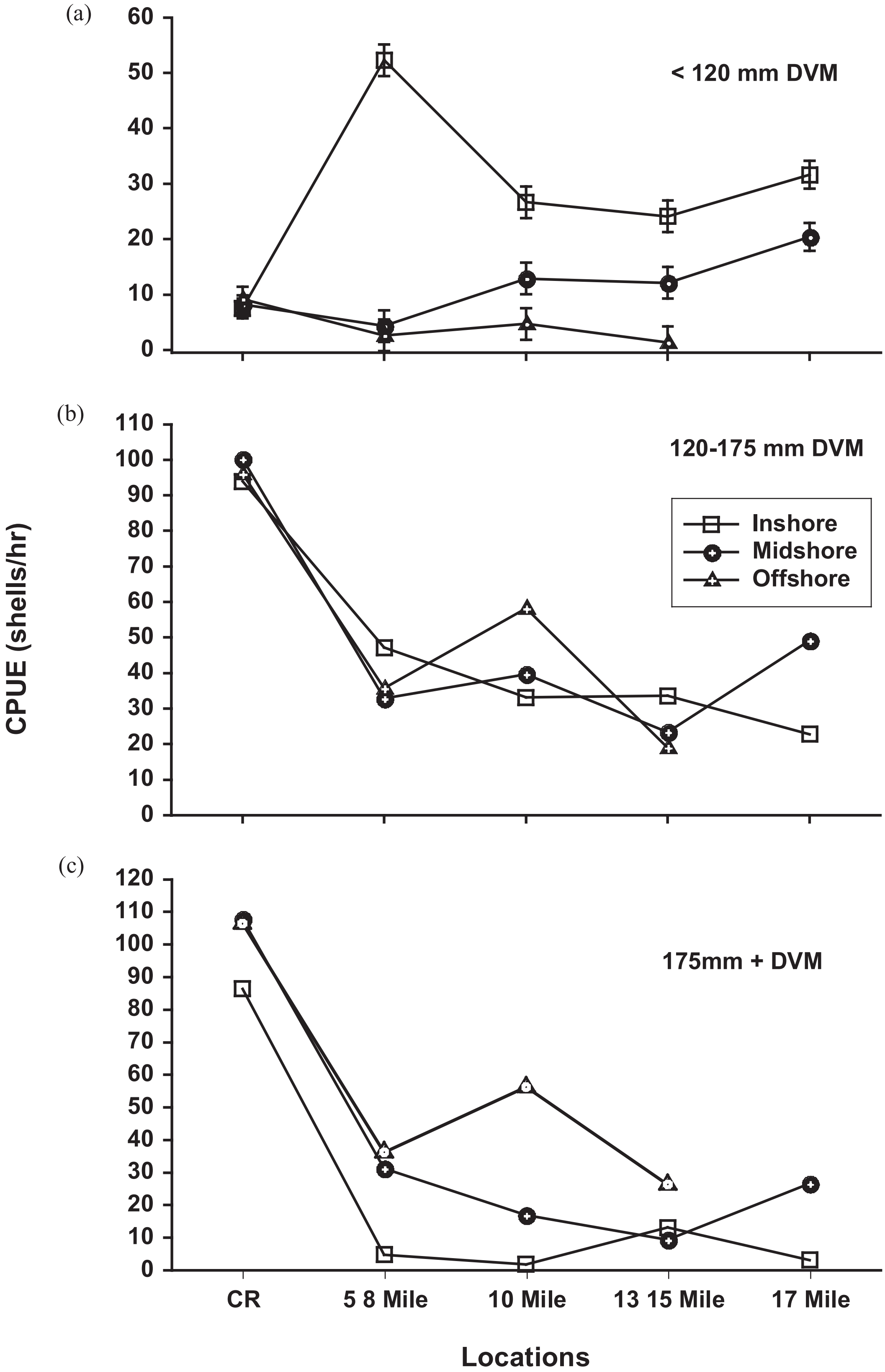


Figure 20. Catch per unit effort for undersize (a), culture size (b), and MOP shell (c) of *Pinctada maxima* at inshore (9-11 m), midshore (15-17 m) and offshore (17-19 m) sites within shallow (5-8 Mile….17 Mile) and deepwater locations (CR - Compass Rose) along 80 Mile Beach.

MOP shell (175mm+ DVM)

MOP catch rates differed significantly among sites within locations ($F_{4,89}$,=33.83, P<0.001; Figure 20c). MOP were found at significantly lower catch rates inshore (6.6 shells/hr) than offshore (39.6 shells/hr) at all locations. Midshore sites recorded intermediate catch rates (19.1 shells/hr). At the 10 Mile, catch rates midshore (16.9 shells/hr) were significantly different to both inshore (1.9 shells/hr) and offshore (56.2 shells/hr) sites (Figure 20c). At the 13-15 Mile, midshore catch rates (9.3 shells/hr) were significantly different to those offshore (26.3 shells/hr) but not inshore (13.1 shells/hr). At the 5-8 Mile, catch rates midshore (31.2 shells/hr) were significantly different (Tukey's P<0.01) to those inshore (4.8 shells/hr), but not offshore (36.2 shells/hr). Catch rates for MOP shell differed significantly ($F_{4,89}$,=2.63, P<0.05) between the best and worst divers, with the others being equal.

4.7.1.2 Deepwater pearl grounds (Compass Rose)

Total Abundance

Divers fishing at locations within the deepwater pearling grounds, where dive times were shorter than allowed in shallow water, collected a mean (range) of 86 pearl oysters per dive (min 61 shells, max 110 shells). This scaled to a mean catch rate of 205.7 shells per hour (min 170.4 shells/hr, max 226.4 shells/hr). Divers caught significantly ($F_{2,18}$=4.16, P<0.05, Tukey's P<0.05) more oysters midshore (216.2 shells/hour) than inshore (187.3 shells/hour; Figure 19). Offshore catch rates (211.6 shells/hour) were not significant different to the other two sites.

Undersized shell (< 120mm DVM)

Undersize shell in the deepwater grounds were scarce, averaging less than 10 shell per hour (Figure 20a). There was no significant difference ($F_{2,18}$,=0.18, P=0.83) in catch rates among sites (7.5 shells/hr inshore, 8.2 shells/hr midshore, 9.2 shells/hr offshore, Figure 20a).

Culture shell (120-175mm DVM)

Catch rates of culture shell at Compass Rose (mean = 96 shells/hr) were almost three times as high as catch rates in the shallow pearl grounds (Figure 20b). No significant ($F_{2,18}$,=0.61, P=0.55) difference in catch rate of culture shell was detected among sites (93.9 shells/hr inshore, 100.2 shells/hr midshore, 96.0 shells/hr offshore).

MOP shell (175mm+ DVM)

Catch rates of MOP sized pearl oysters were significantly higher compared to the shallow grounds (Figure 20c). Within Compass Rose, catch rates inshore (86.4 shells/hour) were significantly (Tukey's P=0.01) lower than those midshore (107.8 shells/hour; Figure 20c).

4.7.2 Size structure

The average length of pearl oysters caught in the shallow water pearling grounds was 148.2 mm DVM (±0.38 SE, n=8489) with a range of 24mm – 252mm DVM (Figure 18). Overall, there was a significant difference in length between inshore (127.6mm ± 0.51 SE; n=3356), midshore (152.8mm ± 0.58 SE; n=2672), and offshore (171.4mm ± 0.60 SE; n=2461) locations (Figure 24). This difference is clearly shown in data from 5-8 Mile (Figure 21), 10 Mile (Figure 22) and 13-15 Mile (Figure 23).

The average length of pearl oysters caught at Compass Rose was 172.9mm DVM (±0.61SE, n=2314) with a range of 27 mm –248 mm DVM (Figure 18). There was no significant difference

($F_{2,2311}=0.62$, $P=0$ 54) in the mean lengths of oysters caught among sites in the deepwater location (Figure 24).

There was a significant interaction ($F_{4,7371}=111.2$, $P<0.001$) between locations and sites at the three locations (5-8, 10, 13-15 Mile) where inner, mid, and outer habitats were sampled (Figure 24). Inshore sites held significantly smaller oysters (average =128.5 mm DVM) than offshore sites (average =172.1 mm DVM), but there was no significant difference between these inshore sites and midshore sites at one of the three locations (Figure 24). At three of the four shallow water locations, pearl oysters were significantly smaller (Tukey's $P<0.001$) at the inshore sites than the midshore sites, the exception being 13-15 Mile where no significant difference was found (Tukey's $P=0.64$; Figure 24).

Trends emerged among 'in', 'mid' and 'out' sub-samples within drifts that ran perpendicular to the shoreline. In a 3 way ANOVA (location x site x sub-replicate) there was a significant interaction in the average length of oysters between the 3 main effects ($F_{8,7353}=5.0$, $P<0.001$). Oysters fished from sub-replicates closest to the shore ('in') were significantly (Tukey's $P<0.05$) smaller than from the sub-replicates fished furthest from the shore ('out') at 2 of the 3 locations (5-8 and 13-15 Mile) at inshore sites (Table 9). At midshore sites of the 10 and 13-15 Mile, oysters sampled from 'in' sub-replicates also had a significantly smaller mean length than those from 'out' sub-replicates (Table 9). No significant differences in length of oysters was detected between inshore sub-replicates at the 17 Mile location, however, midshore samples followed the same trend shown previously; oysters from 'in' sub-replicates (143.8 mm DVM) were significantly smaller (Tukeys $P<0.001$) than those from 'out' sub-replicates (157.2 mm DVM; Table 9).

Culture size oysters were also significantly smaller at sites sampled closer to shore (location x site interaction, $F_{2,3608}=53.4$, $P<0.001$), with a significant increase (average 14.2mm DVM) in length detected between inshore and offshore sites at the three shallow water locations analysed (Figure 25). Mean lengths of culture shell were similar between the offshore sites in the shallow grounds, and the deepwater Compass Rose grounds (Figure 25a).

Analysis of MOP catch lengths (Figure 25b), revealed a similar significant trend among sites ($F_{2,2087}=30.6$, $P<0.001$) and locations ($F_{2,2087}=4.2$, $P<0.05$) to "all shell" captures. MOP oysters were significantly (Tukey's $P<0.001$) smaller inshore (186.2 mm DVM) than midshore (189.8 mm DVM). Offshore samples were the largest (193.4 mm DVM) and were significantly (Tukey's $P<0.001$) larger than both inshore and midshore samples (Figure 25b). The largest MOP sampled were at 5-8 Mile (191.2 mm DVM) and 13-15 Mile (190.3 mm DVM; Figure 25b). Mean size of MOP at the 10 Mile was significantly smaller (188mm DVM).

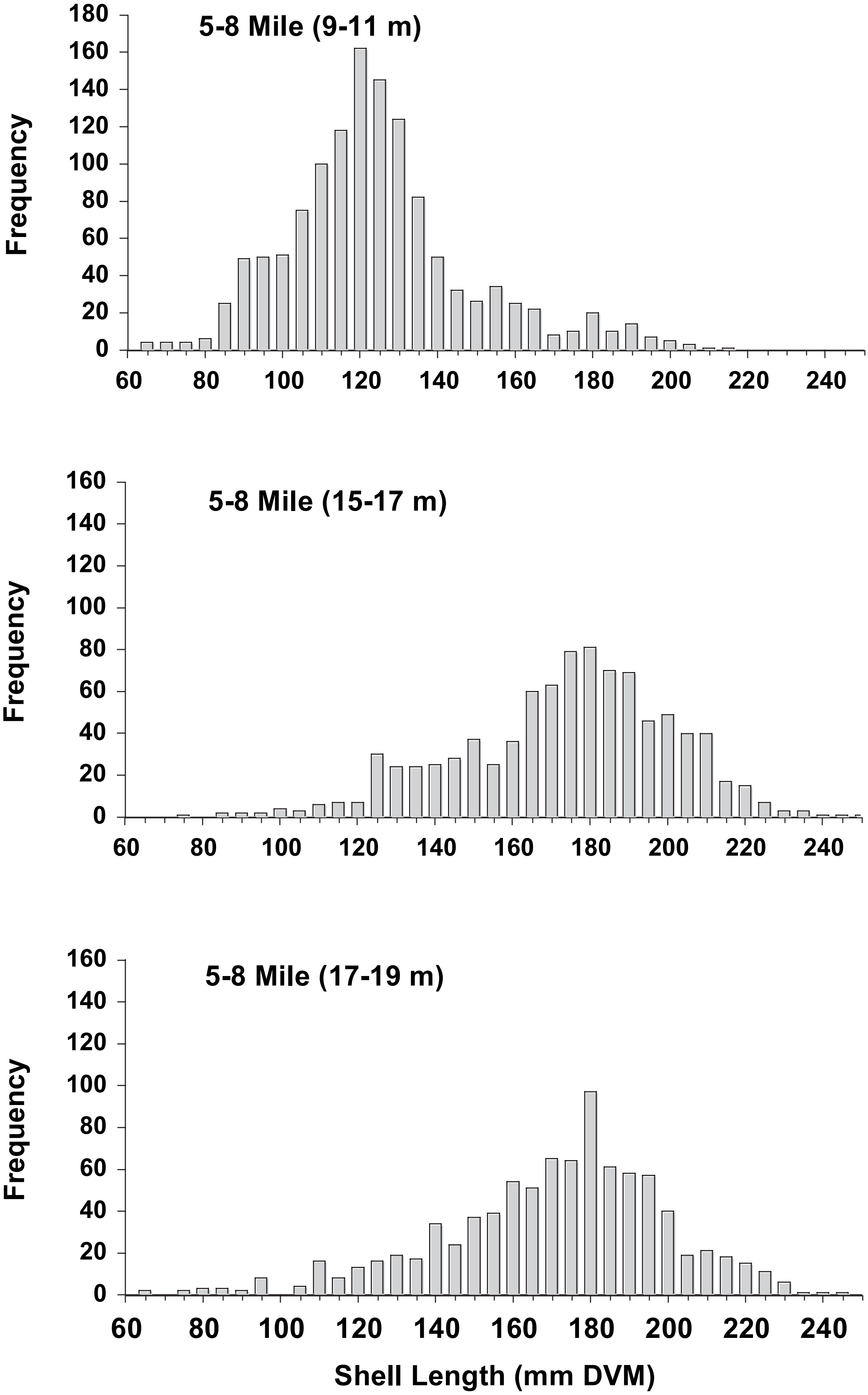


Figure 21. Population structure of *Pinctada maxima* from inshore (9-11 m), midshore (15-17m) and offshore (17-19m) sites at 5-8 Mile.

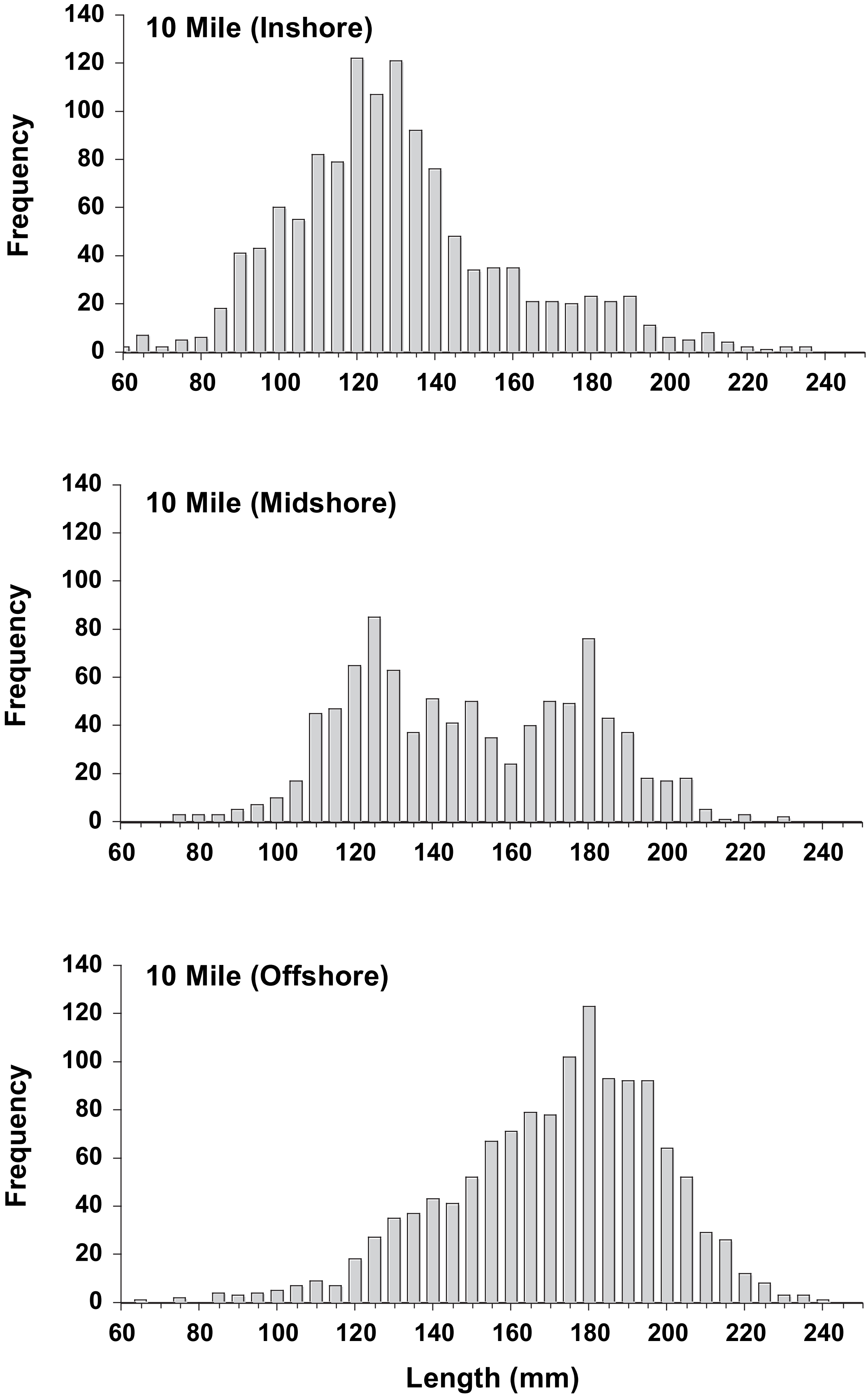


Figure 22. Population structure of Pinctada maxima from inshore (9-11 m), midshore (15-17m) and offshore (17-19m) sites at 10 Mile.

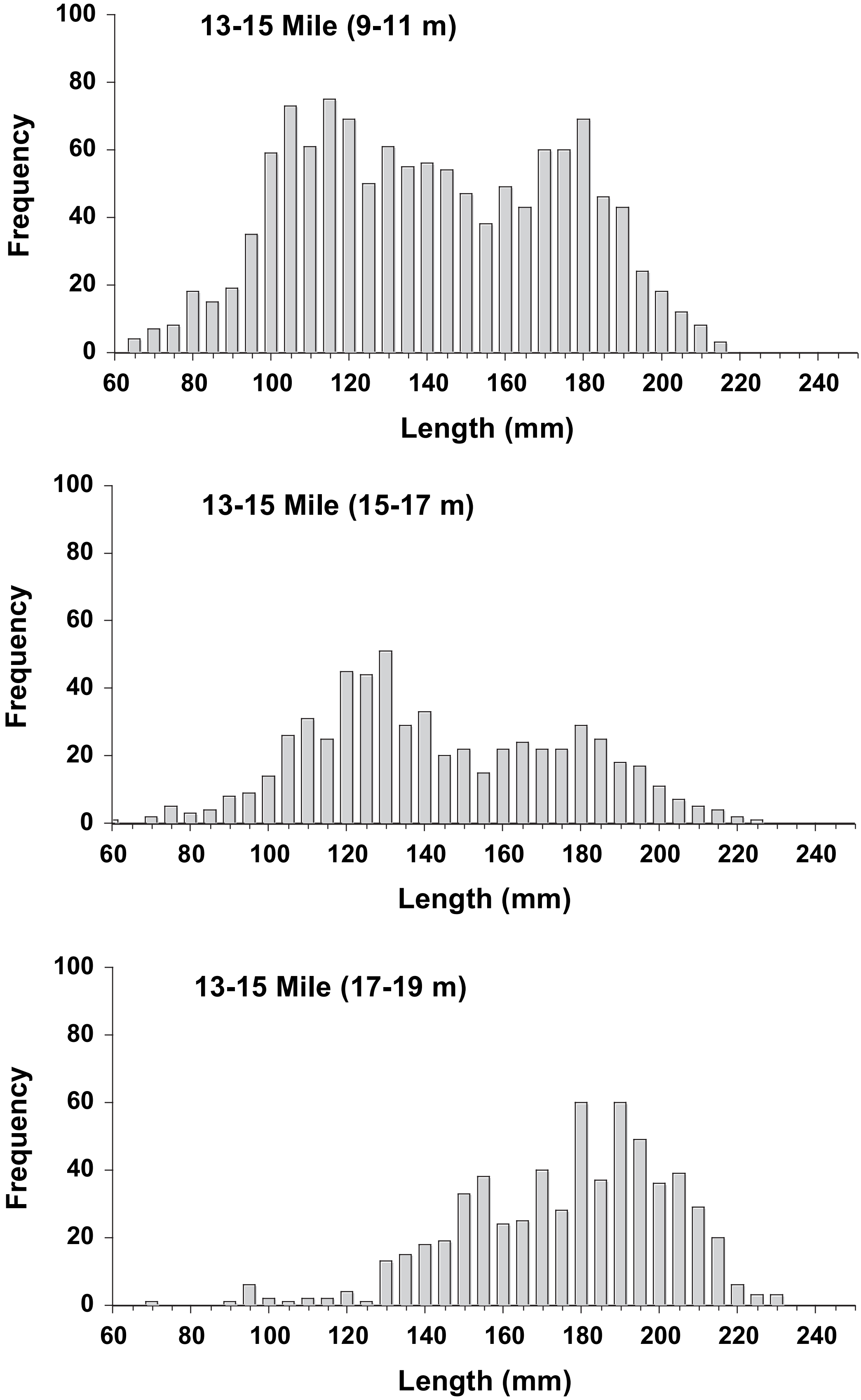


Figure 23. Population structure of *Pinctada maxima* from inshore (9-11 m), midshore (15-17m) and offshore (17-19m) sites at 13-15 Mile.

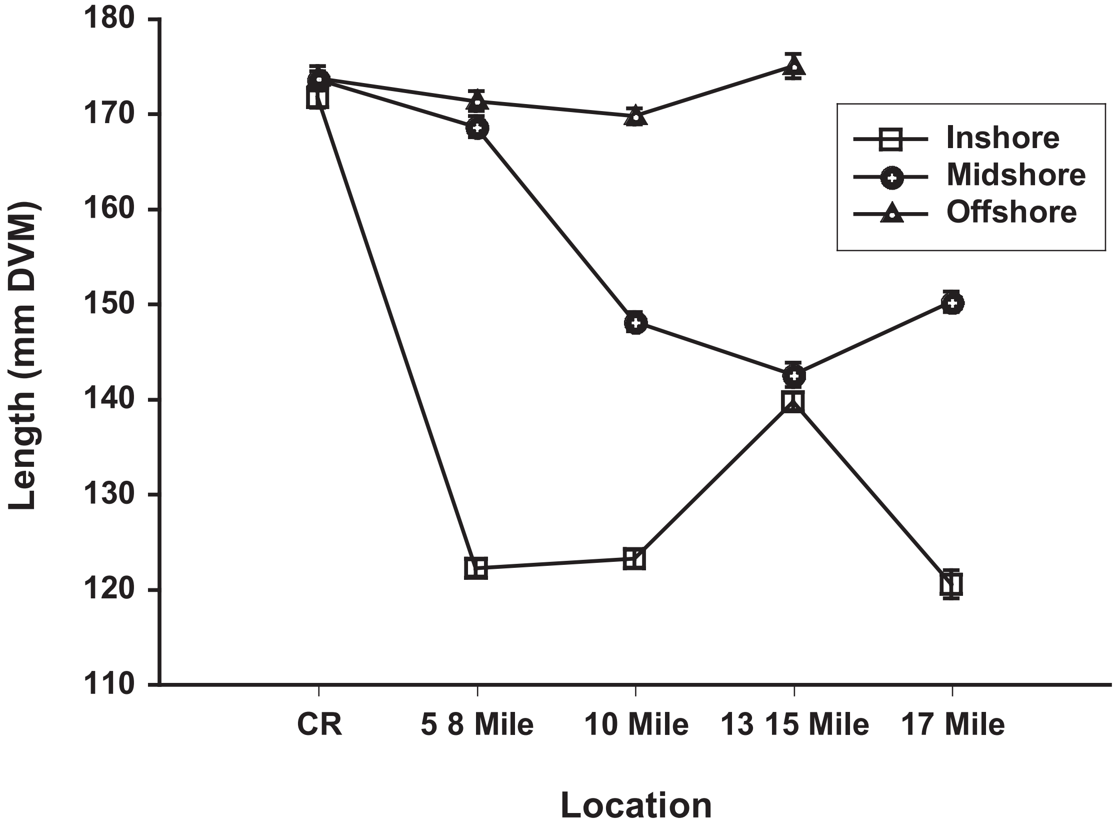


Figure 24. Average length (mm DVM; ± SE) of *Pinctada maxima* from inshore (9-11 m), midshore (15-17 m) and offshore (17-19 m) sites within shallow (5-8 Mile….17 Mile) and deepwater locations (CR - Compass Rose) along 80 Mile Beach.

Table 9. Trends in average size (mm DVM) of *Pinctada maxima* from drifts running perpendicular to the shoreline. Means with the same subscripts do not differ significantly (Tukeys >0.05). Subscript letters only correspond to means within site sub-sample blocks and don't refer to significance between blocks.

Site	Sub-sample	5 8 Mile	10 Mile	13 15 Mile	17 Mile
Inshore	"in"	120.8a	120.2a	128.7a	120.5a
Inshore	"mid"	120.1a	126.7a	138.9b	119.1a
Inshore	"out"	129.3b	121.6a	150.6c	121.7a
Midshore	"in"	168.5a	141.8a	130.4a	143.8a
Midshore	"mid"	167.5a	148.6ab	144.8b	151.8ab
Midshore	"out"	170.5a	152.5b	147.5b	157.2b
Offshore	"in"	168.5a	167.0a	171.3a	
Offshore	"mid"	173.4a	170.5a	176.1a	
Offshore	"out"	172.6a	174.3a	176.7a	

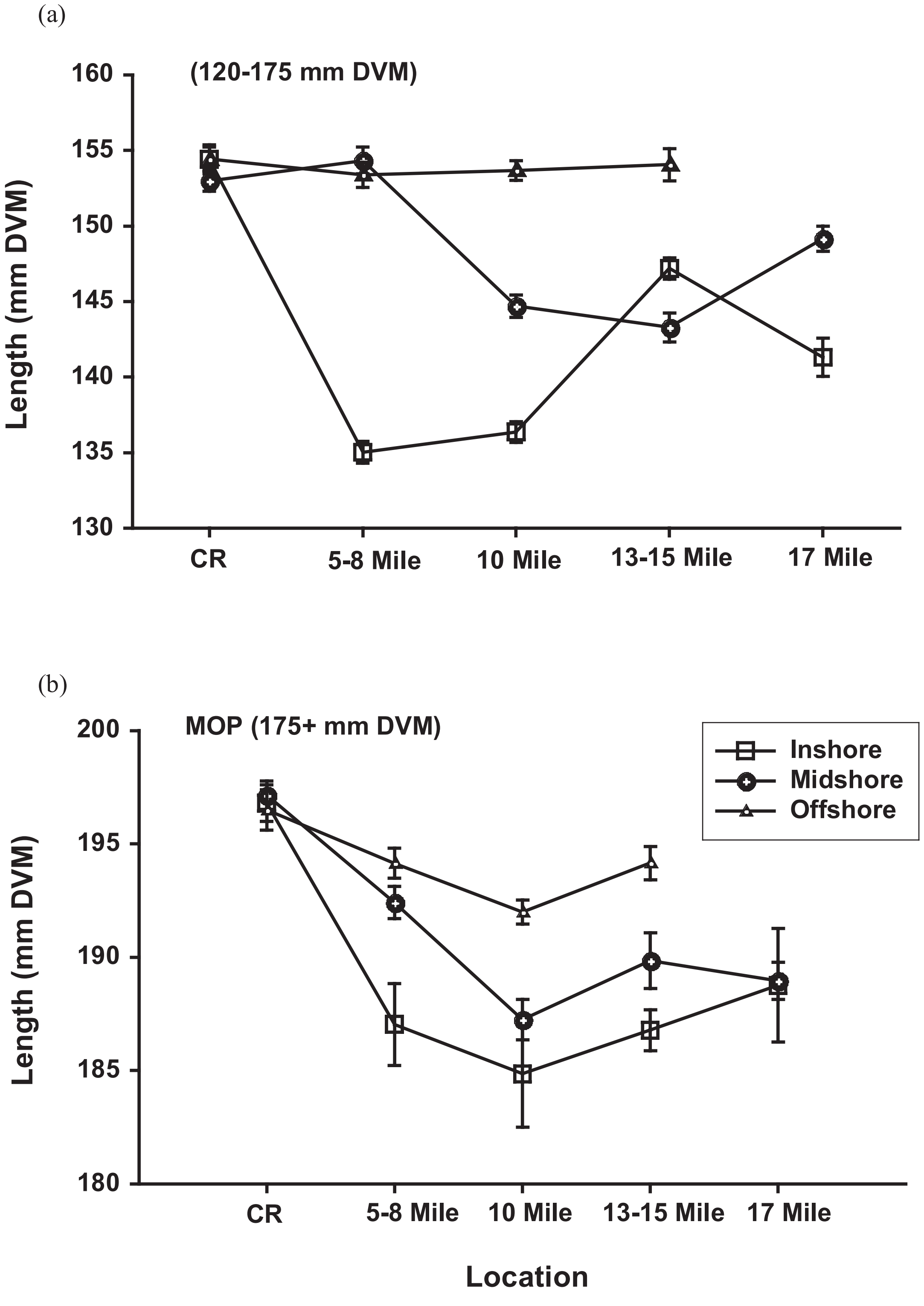


Figure 25. Average length (mm DVM; ± SE) of a) culture sized, and b) MOP of *Pinctada maxima* from inshore (9-11 m), midshore (15-17 m) and offshore (17-19 m) sites within shallow (5-8 Mile….17 Mile) and deepwater locations (CR - Compass Rose) along 80 Mile Beach.

4.8 Quality of MOP Shell

4.8.1 Cliona ***infection***

North of Broome

Of the 2356 pearl oysters sampled at the midshore and deepwater locations north of Broome, 66% had indicators of *cliona* infection. Infection was most apparent on larger oysters, with the proportion of oysters with I and II grade levels of infection most commonly found in culture and MOP sized oyster (Figure 26).

For culture size oysters, the Baleine Banks deepwater location had the lowest infection rate of *Cliona* (8%), followed by Hama Patch (12%), Gantheume (14%), and Lacepede Channel (18%). Carnot Point had the highest infection rate (40%).

For MOP oysters, Hama Patch had the lowest infection rate of *Cliona* (77%), followed by Baleine Banks (78%), Lacepede Channel (88%), and Gantheume (91%). Carnot Point and South Lacepede had the highest infection rate (95% and 99% respectively).

South of Broome

Of the 10,803 pearl oysters sampled at the shallow water 80 Mile Beach and deepwater Compass Rose, 58% had indicators of *cliona* infection. Infection was most apparent on larger oysters, with the proportion of oysters with first and second grade levels of infection most commonly found in culture and MOP sized oysters (Figure 26).

There was a far lower occurrence of category II infection rate from 80 Mile beach pearl grounds, compared to the north of Broome grounds (Figure 26).

Ratios of infected (I and II) to uninfected (0) oysters increased consistently with shell size; undersized (4 % to 8 %; inshore to offshore averages), culture shell (27 % to 35 %; inshore –offshore averages), MOP (84 % to 83 %; inshore to offshore averages) (Table 11).

There was a distinct depth-related trend (as represented by inshore-offshore averages) in *Cliona* infection rate. The 13-15 Mile also had higher rates of infection for culture shell size classes both inshore and midshore. Although significant variation was established among locations and sites, the variation in rate of infection for particular size classes was relatively small, at approximately 15 % for culture shell, 10 % to 15 % for MOP.

Rates of *Cliona* infection on shell from deepwater was 17 % and 13 % higher for culture shell and MOP, respectively, compared to those from shallow water (Table 11)

Table 10. Percentage of shell measured (including *n*) with grades of *cliona* infection north of Broome

Infection Grade	Lacepede Channel	Hama Patch	South Lacepede	Carnot Bay	Carnot Point	Baleine Bank	Gantheaume
All							
n	1127	576	251	32	159	39	172
Culture							
n	552	151	31	1	16	13	28
0	81.7	88.1	61.3	100.0	60.0	92.3	85.7
1	15.6	10.6	29.0	0.0	40.0	7.7	14.3
2	2.7	1.3	9.7	0.0	0.0	0.0	0.0
MOP							
n	417	364	211	31	138	23	140
0	11.8	22.7	1.4	3.2	5.1	21.7	8.6
1	28.8	40.8	17.5	32.3	31.9	30.4	33.6
2	59.5	36.4	81.0	64.5	63.0	47.8	57.9

4.8.2 Recovery of MOP shell retained for nacre sales

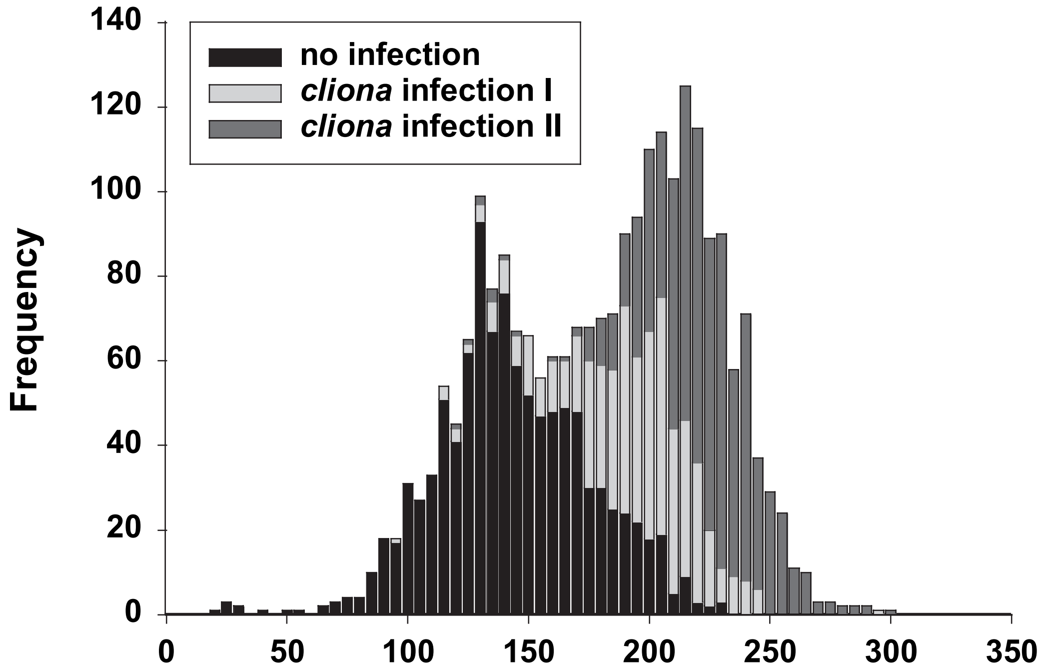
North of Broome, between 10 % - 47 % of MOP were retained for sale; 47% of Hama Patch MOP shell were retained but only 10 % of South Lacepedes MOP (Table 12). Overall, 32% of MOP shells from the North of Broome were of saleable quality (Table 10).

The conversion of caught size to packing size (following chipping of the shell margin) reduced the DVM substantially, from between 8.1 % to 17.7 % of original size. The average from 160 shell measures (range of 175.5 mm – 220 mm DVM) was 23 mm DVM (11.8%) removed from a 193.1 mm DVM shell.

The two valves did not return the same length of nacre when measured from the base of the nacre at the hinge of the valve to the margin of the nacre at its dorsal edge. Nacre length on 101 shells (mean 194.2 mm DVM) averaged 3.7 mm shorter on the flat valve (average 139.9 mm) than the round valve (average 143.6 mm).

Overall, Hama Patch had the lowest overall infection rates and highest recovery of MOP for shell nacre.

(a)



(b)

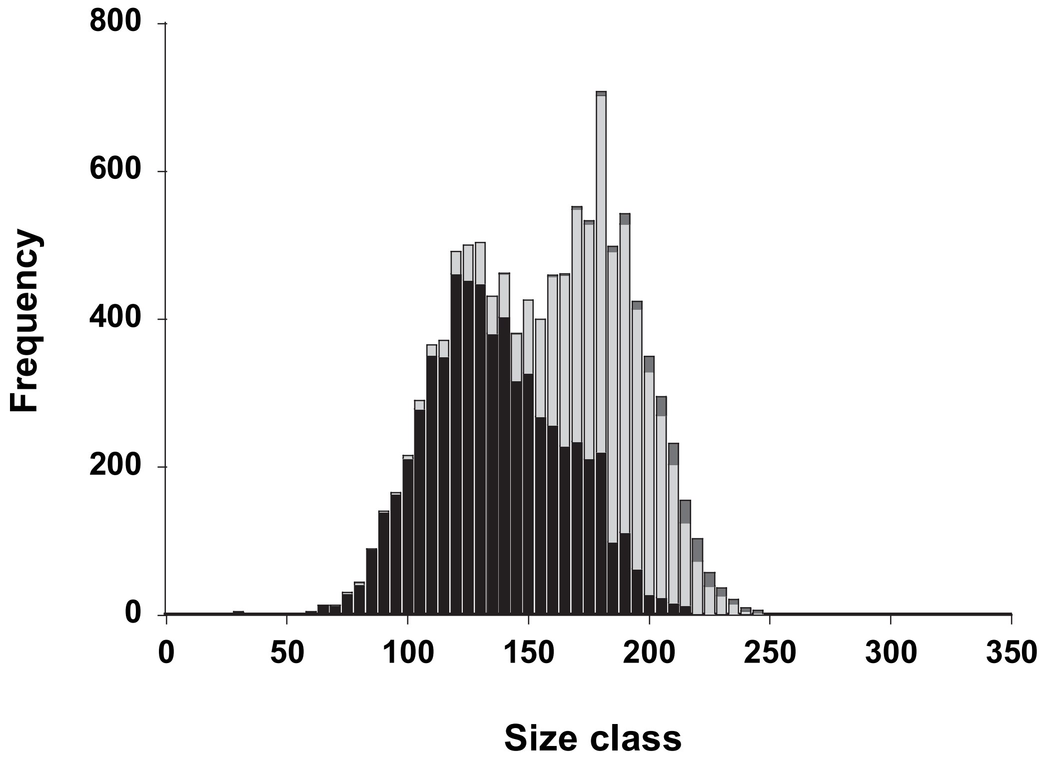


Figure 26. Level of cliona infection of *Pinctada maxima* from a) locations north of Broome, and b) 80 Mile beach and Compass Rose. Description of infection grades is found in the methods

Table 11. Percentage of *Pinctada maxima* on 80 Mile Beach with different grades of *cliona* infection. Size classes in mm DVM

Size Class		Inshore (9-11 m)			Midshore (15-17 m)			Offshore (17-19 m)			Average		
	Infection	**0**	**1**	**2**	**0**	**1**	**2**	**0**	**1**	**2**	**0**	**1**	**2**
< 120mm	5 8 Mile	95	5	0	95	2	2	100	0	0	97	2	1
	10 Mile	95	6	0	100	0	0	87	13	0	94	6	0
	13 15 Mile	96	4	0	95	5	0	100	0	0	97	3	0
	17 Mile	98	2	0	99	1	0				98	2	0
	Average	96	4	0	98	2	0	92	8	0			
120-175 mm	5 8 Mile	86	14	0	66	34	0	70	30	0	74	26	0
	10 Mile	79	21	0	79	21	0	67	33	0	75	25	0
	13 15 Mile	64	36	0	65	35	0	70	30	0	66	34	0
	17 Mile	73	27	0	82	18	0				78	22	0
	Average	73	27	0	70	30	0	65	35	0			
MOP													
	5 8 Mile	27	71	2	21	69	10	22	70	8	23	70	7
	10 Mile	29	64	7	26	72	3	16	82	2	24	73	3
	13 15 Mile	21	78	1	10	90	0	22	78	0	18	82	0
	17 Mile	24	76	0	30	69	1				27	72	1
	Average	16	79	5	17	74	9	17	78	5			
Size Class			**Inshore (30 m)**			**Midshore (32 m)**			**Offshore (33-34 m)**			**Average**	
	Infection	**0**	**1**	**2**	**0**	**1**	**2**	**0**	**1**	**2**	**0**	**1**	**2**
< 120mm	C Rose	96	4	0	100	0	0	87	13	0	94	6	0
120-175 mm	C Rose	59	40	0	57	42	1	50	48	1	56	43	1
MOP	C Rose	9	83	8	8	78	14	8	81	11	8	81	11
	Average	38	58	4	34	58	8	31	63	6			

Table 12. Shell quality (measured by % MOP kept for sale) at locations North of Broome.

Location	Position	Depth	MOP caught	MOP kept	% MOP kept
Lacepede Channel	Mid-shore	16-20 m	417	159	38
Hama Patch	Mid-shore	15-16 m	365	170	47
South Lacepede	Mid-shore	17-18 m	23	9	39
Carnot Bay	Mid-shore	16 m	211	20	10
CarnotPoint	Mid-shore	11-12 m	31	12	38
Baleine Bank	Deep	30-34 m	138	23	16
Gantheaume	Deep	25-30 m	140	34	24
Overall Mean			1325	427	32

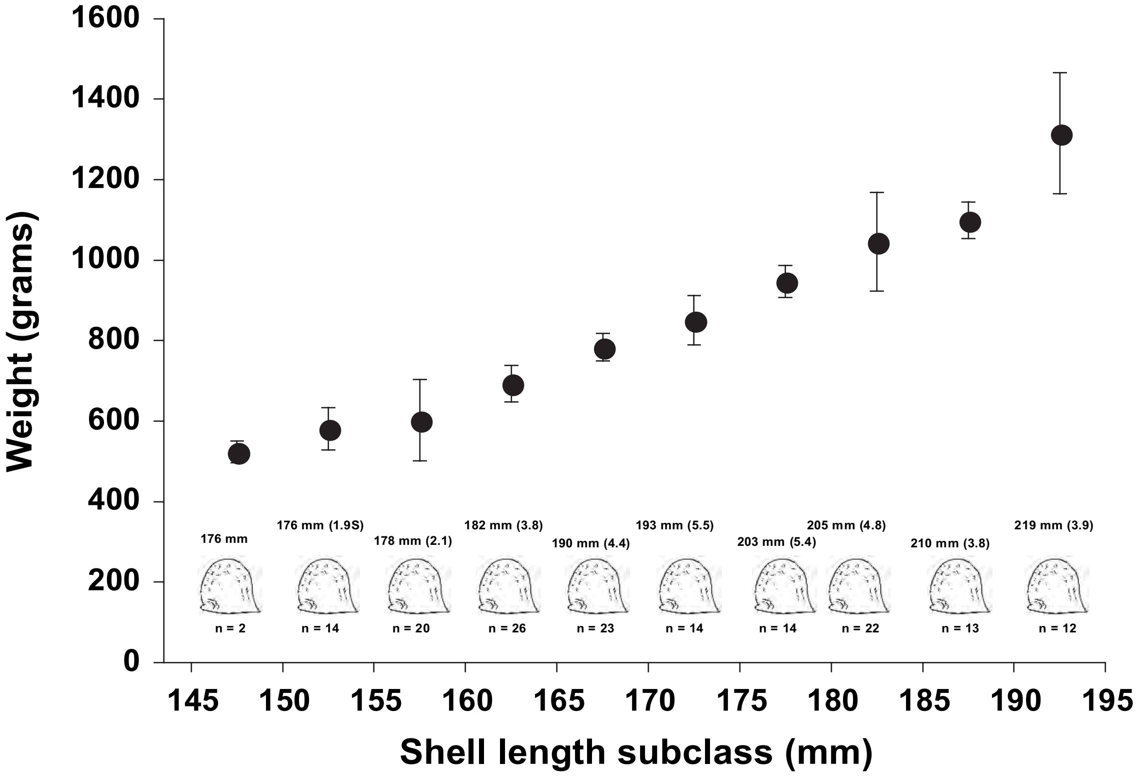


Figure 27. Weight (recovery) of *Pinctada maxima* by shell length after processing for the sale of nacre.

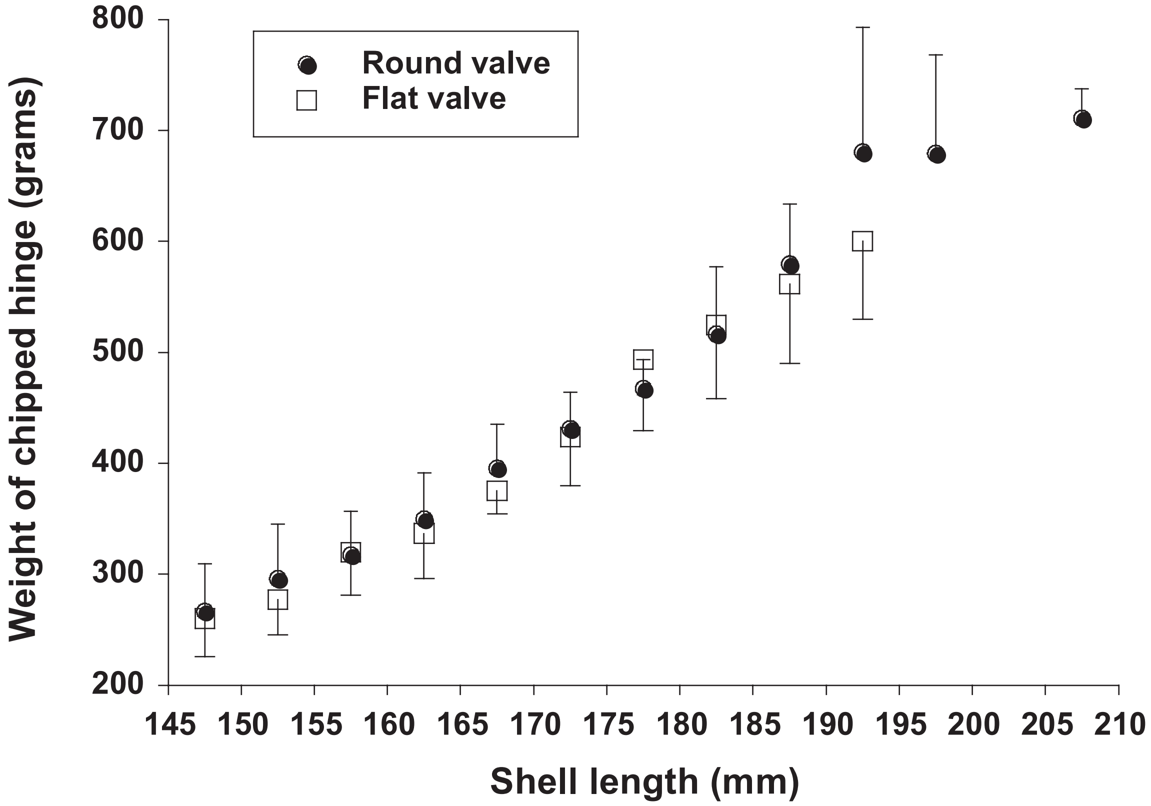


Figure 28. Weight (recovery) of flat and round valves of *Pinctada maxima* shell after processing for the sale of nacre.

Mean dry weight of MOP (shell only, with shell margin removed) taken from the 80 Mile each and Compass Rose varied between 523g and 1.315kg per whole shell, depending on shell size (n = 56, Fig. 27). Average weights of flat and round valves varied between 250 and 700 g depending on shell size (Figure 28).

MOP shell valves were sorted into three grades (B, FAQ, and C). The finest grade used was B, followed by FAQ and the lowest quality C grade. There was no consistent depth related trend in the relative abundance of B grade shell, although the inshore shallow water sites had the lowest average percentage of B grade shell (Figure 29).

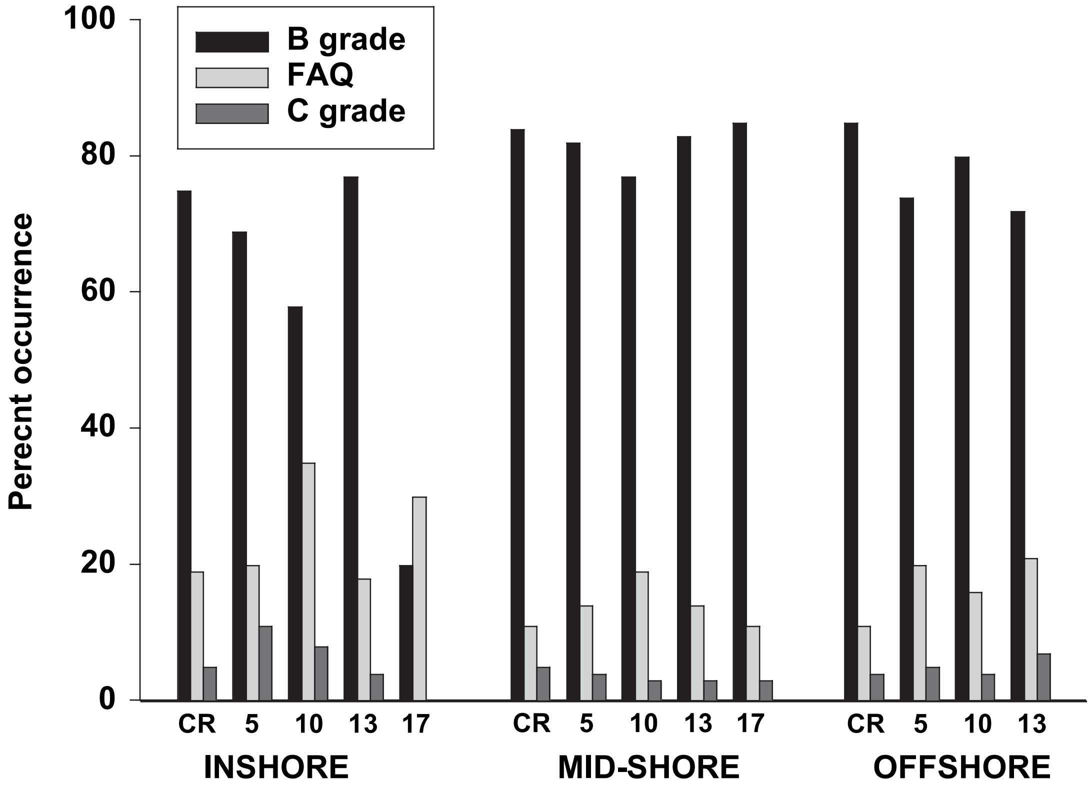


Figure 29. MOP shell grade by location (CR: Compass Rose, 5: 5-8 Mile, 10: 10 Mile, 13: 13-15 Mile, 17: 17 Mile and site (inshore, mid-shore, offshore).

4.9 A review of population connectivity within *Pinctada maxima* stocks

4.9.1 Introduction

A theory of population connectivity is source-sink population dynamics. This postulates habitat-specific demographic (e.g. growth, mortality, reproduction, migration, dispersal) rates, where a ‘source’ habitat, at equilibrium, shows no net change in population size, but is a net exporter of individuals, and similarly, a ‘sink’ area at equilibrium, is a net importer of individuals (Pulliam, 1988). It was formalized mathematically by Pulliam (1988, 1996) and its applicability to marine populations rests on three observations; a) not all habitat is of equal quality for settlement of recruits; b) the great majority of marine species have a dispersal larval phase that lasts anywhere between a day and 12+ months (some lobster species - *Jasus edwarsii*), and c) ocean currents, be they tidal or wind driven, transport eggs and larvae, sometimes for long distances and generate interconnections among areas (Crowder et al., 2000). Oceanic features such as vertical structures of the water column, surface circulation, and upwelling activity produce eddies or disperse larvae, creating source and sink areas (Cole and McGlade, 1998). Hence, high levels of recruitment alone do not solely define the resilience of a population.

Source-sink theory in terrestrial ecology has been applied successfully to evaluate the effectiveness of protected areas, with both theoretical (Pulliam, 1988; Doak, 1995; Gaggiotti, 1996) and empirical studies (Pulliam and Danielson, 1991) demonstrating habitat specific demographic rates for different species and by implication, the possible existence of source-sink dynamics. Some empirical studies have demonstrated areas of annual recruitment surplus and deficit (Blondel et al., 1992; Thompson and Whitfield, 1993). Consequently, it is in the evaluation of siting of Marine Protected Area's (MPAs) that source-sink theory has been most applied within marine population ecology (Crowder et al., 2000).). However, larval dispersal (indexed by ocean currents), rather than habitat-specific demographic parameters, has been the key factor in defining sources and sinks (Lipcius et al., 1997; Roberts, 1997; 1998).

In a recent review, Crowder et al. (2000) cautioned against evaluating source-sink relationships purely on the basis of ocean currents, because their complexity and unpredictability hinders attempts to back-track dispersed larvae to their physical source. Instead they eschewed the classic definition of sources and sinks – areas of varying demographic rates influenced primarily by differences in habitat quality - in order to evaluate the citing and placement of MPAs. The primary reason for this approach is that habitat quality is likely to be much more temporally stable than environmentally driven ocean dynamics and the ensuing larval transport (Cowder et al., 2000).

The implicit assumption underlying the current favour of source-sink population theory is that separated source and sink areas are more common than the alternative situation, i.e. that populations are simultaneously both source and sink. However, it is the latter situation that is likely to be more common. In a review, Roberts (1998) found that assessment of 'upstream' and 'downstream' reefs (based on maps of surface currents) yielded few locations that fell into either of these extremes, and most reefs had areas of both 'upstream' and 'downstream' reef. Roberts (1998) also concluded that "not a single reserve (control) could be established on the current knowledge of connectivity patterns in the sea, highlighting the difficulty in developing a connectivity map of source and sink areas in any fishery.

To set the background to our assessment, we review specific examples of source-sink dynamics in marine invertebrates and examine connectivity in *Pinctada maxima* populations, focusing on genetic evidence, oceanographic studies, adult and juvenile densities, and available habitat information. We asked whether the population structure of *P. maxima* confirms the possibility that broodstock in deep waters are sufficiently abundant to support inshore stocks? This led to consideration of the potential significance of source-sink dynamics, should they exist, to the sustainability of the fishery. Recommendations were provided on methods to empirically test the hypothesis.

The resilience of the *Pinctada maxima* fishery in Western Australia (over 100 years of commercial fishing) makes it an ideal candidate for testing of source-sink theory. This can be compared with major populations of *P. maxima* that once existed in the Torres Strait in Queensland (Ward, 1993), and the Northern Territory (Knuckey, 1998).

4.9.2 Source-sink dynamics in marine invertebrates - examples

<u>Crown of thorns starfish</u> (*Acanthaster planci*)

An example of the interplay between adult abundance, recruitment success, habitat quality (i.e. coral community structure) and ocean currents is provided by the crown-of-thorns starfish (COTS), which has undergone periodic population explosions on the Great Barrier Reef and many other parts of the Indo-Pacific (Lourey et al., 2000; Sano, 2000; Fong and Glynn, 1998; Reichelt et al., 1990; Moran, 1986; Done, 1992). Many aspects of COTS biology and population dynamics have been studied and provide insight into the nature of source-sink dynamics in marine invertebrate populations.

Acanthaster planci is a specific echinoderm predator on Indo-Pacific coral reefs with a clear preference for tabular corals of the genus *Acropora* (De'ath and Moran, 1998). It reproduces externally, producing between 20 and 60 million eggs (Moran, 1986), the larvae move through six stages of development lasting 3-4 weeks before settling onto corralline algae within reef systems. Its diet turns wholly corallivorous by 6 months of age, after an initial feeding on diatoms and other particulate organic matter, and reaches sexual maturity at approximately 2 years.

Over the past 40 years, a number of population outbreaks of *Acanthaster planci* occurred on the Great Barrier Reef, precipitating southward propagating waves (Benzie and Wakeford, 1997a; Reichelt et al., 1990; Kenchington, 1987; Endean, 1973). Through a combination of empirical data on adult abundances, oceanographic modelling, and genetic studies, an outbreak process was identified that can be interpreted in terms of source-sink theory. A primary source population between 14 and 16°S in the northern section of the Great Barrier Reef was hypothesised to have initiated the outbreaks (Benzie and Wakeford, 1997b; Reichelt et al., 1990), although the requirement for a northern source population was initially disputed (van der Lann and Hogeweg, 1992). However, recent genetic studies comparing two out-breaking populations separated by 10+ years (1986 vs 1996), confirmed the hypothesis of a single genetic source (Benzie and Wakeford, 1997).

Through larval drift in prevailing oceanographic currents, secondary source populations were created which in turn fed larvae into reefs further south where suitable habitat was available, and the population explosions slowly moved southward over a period of a few years (Reichelt et al., 1990), until suitable habitat (high abundance of preferred coral species) was no longer available. The "south-ward drift" hypothesis was supported by long-term data from annual *Acanthaster* surveys (Lourey et al., 2000), oceanographic modelling (Black et al., 1995.), and habitat surveys of the outbreaking reefs (Ninio et al., 2000). Numerous studies showed significant decreases in density of live coral (the primary food source) after population outbreaks (Lourey et al., 200; Colgan, 1987; Done, 1992, Done et al., 1988.). However, the lack of finer scale data on localised current dynamics and habitat type meant that many of the anomalies in the overall pattern (e.g. extreme patchiness of outbreaks within individual reefs, and between adjacent reefs) were not explained.

From the point of view of source-sink theory, there are a number of key issues that highlight the process. First, there was an original source population upstream of the sink populations, although the specific location could not be pinpointed accurately and may have varied over time (Black et al, 1995). Second, that sink populations were created through larval linkages arising from the prevailing oceanic currents, which then became sources for population outbreaks, and subsequent release of larval offspring into the south-ward drifting flow. Third, the habitat quality (defined by abundance of the preferred coral food sources) had a large influence on the extent and nature of the outbreaks. Thus, it appears for *A. planci*, source-sink dynamics link populations and create population explosions when habitat quality is at certain levels. These dynamics may also be operating at much reduced scales when population levels are normal.

<u>Carribbean spiny lobster</u> (*Panulirus argus*)

Panulirus argus supports the most valuable invertebrate fishery throughout the Cariibbean (Bohnsack et al., 1994). It is a nocturnal forager in seagrass beds and reef flats, sheltering during the day under crevices of coral or rocky reefs. Spawned egg masses hatch in the spring and summer, and wind-driven surface currents shift larvae offshore into oceanic habitats where they remain for 4-9 months (Lipcius et al. 1997). The post-larva is a free-swimming, non-feeding stage that migrates inshore where it settles into the benthos. It is this long-larval stage which has the potential to de-couple adult abundance from juvenile settlement and elevate the importance of source-sink dynamics to maintenance of the overall metapopulations.

Lipcius et al. (2001; 1997) examined connectivity between sub-populations of *Panulirus argus* in differing habitats within a deep (> 1km) semi-enclosed basin (approximately 175 × 65 km) called Exuma Sound in the central Bahamas. Using data on post-larval supply, juvenile and adult abundance, and oceanographic modelling at four widely separated sites, they were able to generate a connectivity map and tentatively classify the four sites as sources or sinks. Large-scale eddy fields concentrate and advect postlarvae towards the sink site, which had the highest post-larval supply but lowest adult abundance (Lipcius et al. 1997). The other sites were classified as source sites. Lipcius et al. (1997) concluded that post-larval supply is probably decoupled from adult abundance by physical transport, while adult abundance is likely decoupled from post-larval supply by habitat specific mortality rates within the sites.

Lipcius et al. (2001) used data on lobster abundance, habitat quality, and hydrodynamic transport to assess the success of marine reserves in reducing fishing mortality and protecting the metapopulation. Their conclusion was that use of information on habitat quality or adult density did not yield a higher probably of success than did determining the reserve location by chance, and the only successful strategy was the one that used information on larval transport processes.

4.9.3 Genetic evidence for connectivity

The silverlip pearl oyster, *Pinctada maxima* is a broadcast spawner that produces greater than 30 million viable eggs under hatchery spawning conditions, and whose egg and larval stages spend up to 3 weeks in the plankton. It is widely dispersed within tropical Western Australia and the Indo-Pacific, however the boundaries of commercially fished populations are Exmouth Gulf in the south-west of its range, and Lacepede Channel in the north-east, a distance of about 1200 km. Within these populations, areas fished are discrete and separated by large distances. The first studies of allozyme variation found little variation between Exmouth Gulf and Cape Bossut (80 Mile beach shallow), indicating high connectivity over 800km (Johnson and Joll, 1993). The pattern was consistent with other species along this coastline with planktotrophic larvae (Johnson and Joll, 1993), and is likely to be correlated with the extensive water currents arising from six to twelve metre tidal ranges.

Benzie and Smith (2002) developed microsatellite DNA markers for *Pinctada maxima* and examined connectivity in more detail within WA, Northern Territory and Indonesian populations. They compared Lacepedes, 80 Mile Beach shallow, 80 Mile Beach deep, Port Hedland, and Exmouth Gulf populations, found extensive gene flow and large effective population sizes, and confirmed the hypothesis of high connectivity amongst populations. However, there was some evidence for genetic differentiation between Exmouth Gulf and the more northern populations (Benzie and Smith, 2002).

In summary, commercially fished populations of *Pinctada maxima* in Western Australia are linked closely at a genetic scale. This is certainly the case for shallow and deep populations in the 80 Mile beach region, which are the mainstay of the fishery.

4.9.4 Adult abundance and recruitment

Potential clues indicating the existence of source-sink dynamics are a spatial de-coupling of adult abundance and recruitment as measured by a log-log plot of recruitment vs adult density by location (Lipcius et al., 1997). Minimum shell sizes captured during abundance surveys were 70-80mm DVM (see section 4.5 and 4.6). Thus an appropriate index of recruitment is abundance of 70 to 120mm DVM shell. At 80 Mile Beach, this is mostly the 2+ year class (Hart et al., 1999; Joll, 1996). Adult abundance is the density of MOP (175+ mm DVM) size classes.

Recruitment density (2+ year class) and MOP (175mm+ DVM) density were significantly and negatively correlated ($p < 0.05$; Figure 30a). When analysis is restricted to the inshore stocks (not including Compass Rose), recruitment and MOP density are even more negatively correlated ($r^2 = 0.54$; Figure 30b).

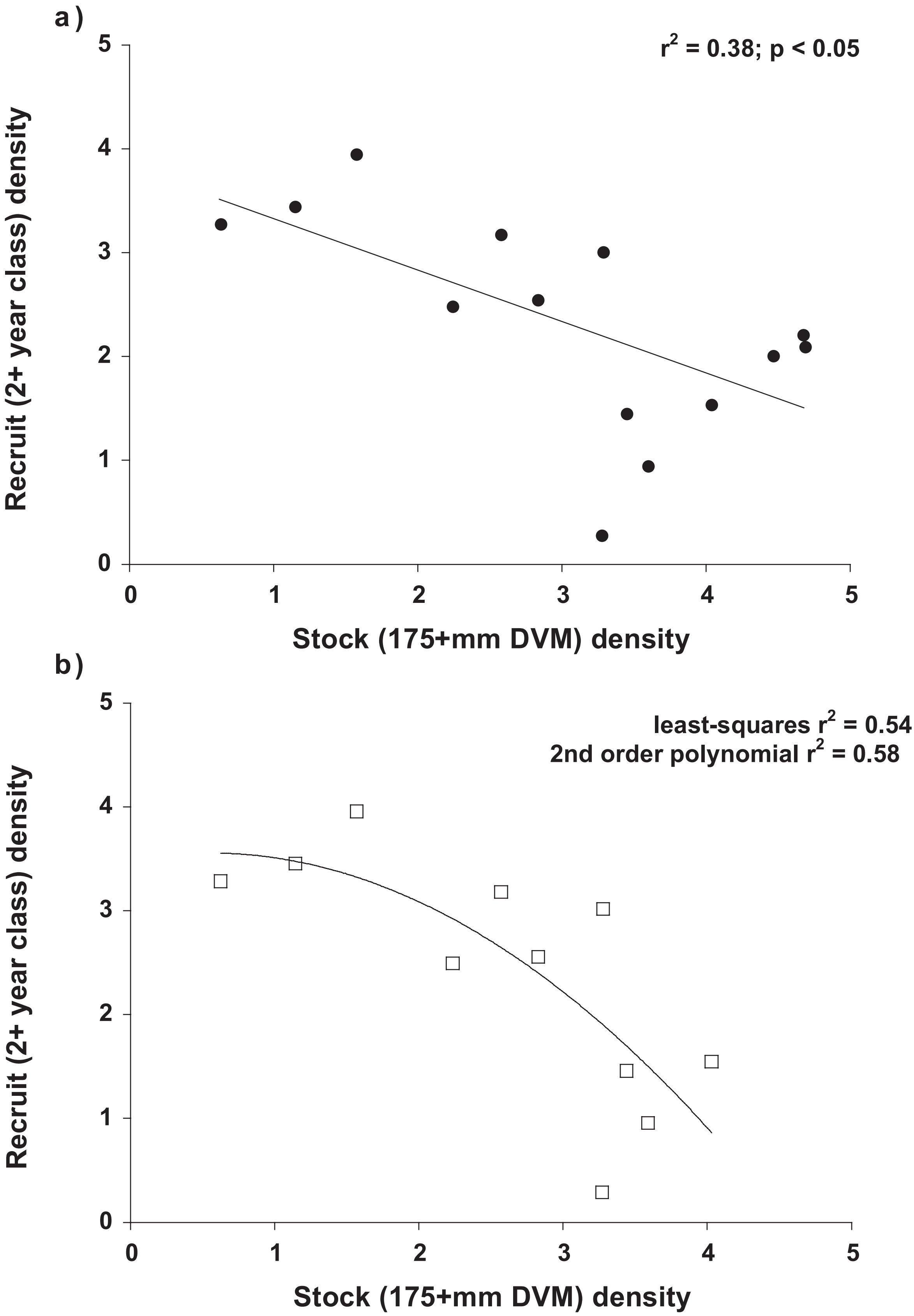


Figure 30. Broodstock (MOP) abundance (log transformed) and recruitment (2+ year class) density (log transformed) of *Pinctada maxima* from stock surveys at (a) 14 shallow and deepwater sites, and (b) 11 shallow water sites only. This is a comparative evaluation and not a stock-recruitment relationship.

There was a positive correlation between depth and abundance of MOP, and a negative correlation between depth and abundance of recruits (Figure 31b), although the relationship is not as clear when the lightly fished deepwater stocks at Compass Rose are included (Figure 31a).

Thus, one potential explanation of the data is that it reflects a de-coupling of brood stock densities from subsequent recruitment in *Pinctada maxima*. The other explanation is that the pattern is reflective of fishing pressure. Highest densities of recruits in the shallowest depths may be a function of hydrodynamics – the coastline is a barrier that limits dispersal and concentrates larvae. The low abundance of MOP in shallow areas is likely caused by high fishing mortality. Average depth fished by the pearling fleet fell from 15-16 m in the early 1990's, down to 11m in 2000, although average depth fished in 2002 was slightly higher at 13.5 m (Figure 32). Shallow areas may also exhibit a higher natural mortality of MOP due to adverse conditions. In contrast, the deep-water sites have a high abundance of MOP, despite lower levels of recruitment, due to the low fishing pressure.

Joll (1996) estimated shell catchability for larger oysters (150-170mm) was 16%, compared to small (120-150 mm) oysters (27%) on "Potato" bottom, which is the main bottom type in shallower areas. Larger oysters were more camouflaged within this habitat and harder to detect. Joll (1996) also showed that catchability was higher (37%) on "Garden" bottom, which is the other major habitat type in the pearl fishery. Detailed data on habitat are being collected as part of a current FRDC project (2000/127), but it appears to be important in understanding density.

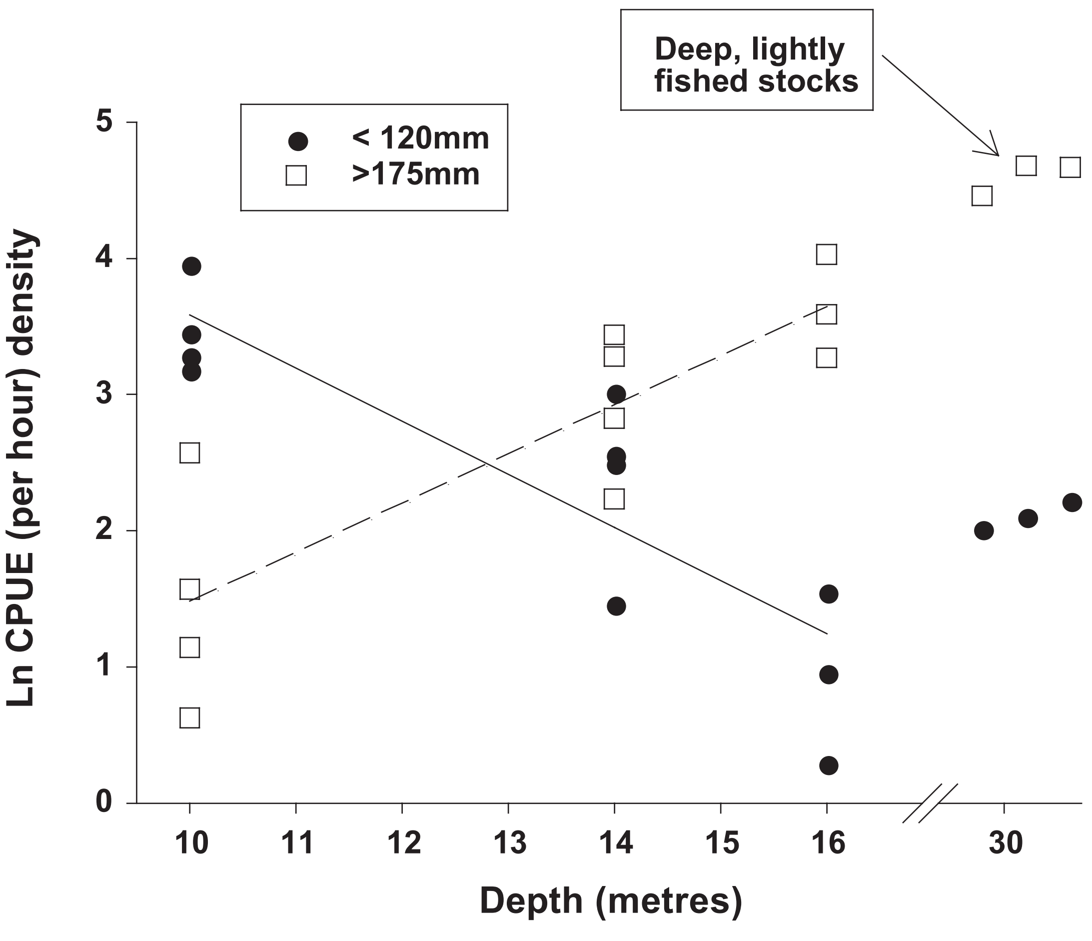


Figure 31. Density of stock (MOP – 175mm + DVM) and recruits (80-120 mm DVM) as a function of depth.

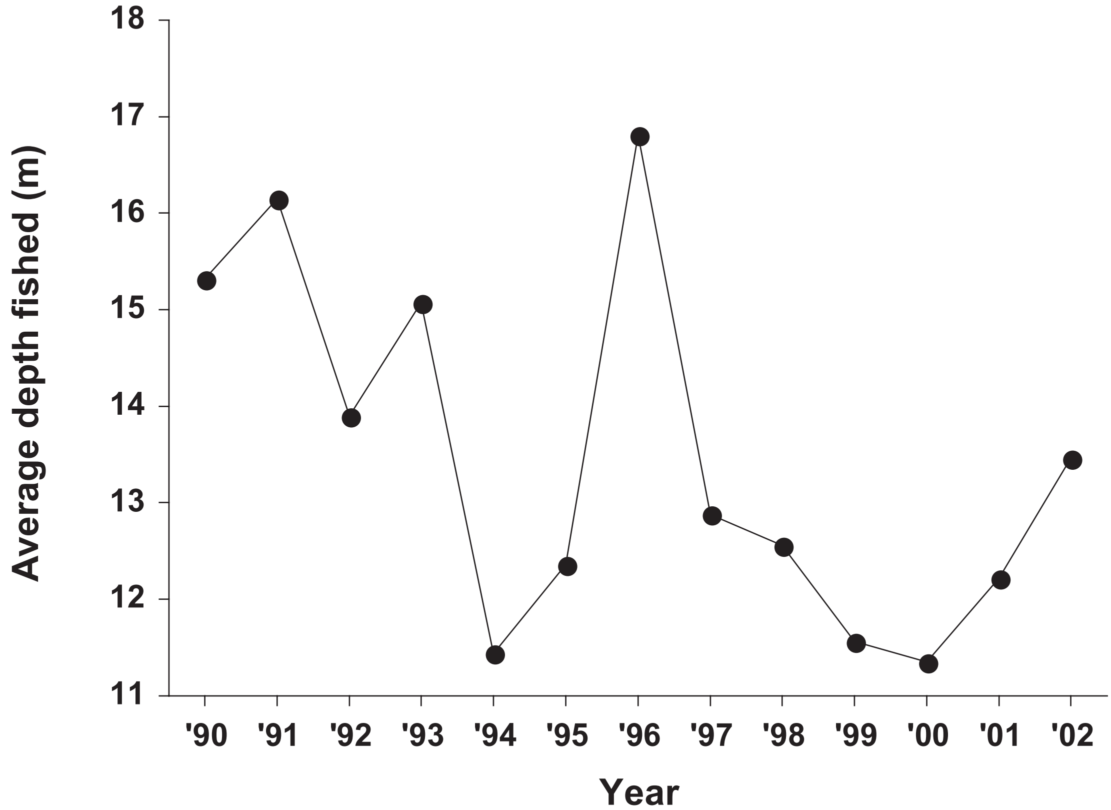


Figure 32. Average depth fished by the pearling fleet in the 80 Mile Beach area during 1990 to 2002.

4.9.5 Methods for testing population connectivity in Pinctada maxima

Oceanographic modelling of larval drift is a well-established methodology for investigating and understanding how species with extended planktonic larval phases maintain themselves at latitude, and become transported to juvenile habitat (Griffin et al. 2001; Sammarco and Heron, 1994). The methodology has facilitated in recent years by ease of access to data from a growing range of remote sensing tools. Oceanographic data such as SSThas been gathered from advanced very high resolution radiometer (AVHRR), upwelling indices from U.S. National Atmospheric Administration (NOAA), wave height and wind information from satellites and buoys (Wing et al. 1998).

An examination of larval sources, drift, and sinks in *Pinctada maxima* populations in the 80 Mile Beach region would utilise existing data from this study and the oceanographic modelling work undertaken as part of the NWSJEMS (North West Shelf Joint Environmental Management Study - www.marine.csiro.au/nwsjems/index.html), information on spatial and temporal spat settlement trends by depth and habitat from current research (FRDC 2000/127), and implement modelling work under the following lines of investigation.

1. Model larval movements for various:
   - spawning locations
   - spawning seasons
   - spawning years (including El Nino & La Nina).

2. Determine sensitivity to:
   - larval duration
   - preferred larval swimming depth.

3. Summarise model results in the form of settlement probability maps.
4. Fit settlement probability estimates from the model to spat settlement data from FRDC project 2000/127 and spatial distribution of capture shell from daily pearl diver logbooks.

Note that at the date of submission of this report, preliminary oceanographic modelling results suggest shallow water sources for most of the spat settlement data (Scott Condie, pers. comm.).

4.10 Protocol for managing future harvesting of MOP

This project has identified a number of fishery and biological issues relevant to any future proposals to harvest MOP.

- The fishery has been commercially fished since the 1890's and historical catches of MOP were substantial, peaking at 2000 tonnes in 1917.
- There has been a total ban on harvest to MOP since the mid-1980's, and most stocks have not been fished for over 20 years.
- Natural mortality is very low, probably under 0.1 in most areas where significant stocks exists, and appears to be negatively correlated with depth, and potentially habitat type.
- *Pinctada maxima* is a protandrous hermaphrodite, and size at sexual maturity (when 50% of the population is mature) for females is between 170 and 180 mm DVM. This fact, combined with the nature of the fishery (which targets 120-170mm), ensures almost complete protection of the breeding stock.
- There appears to be no relationship between fecundity (number of eggs) and size for oysters larger than 180mm DVM. This data is preliminary and needs further confirmation.
- There are a number of areas no longer fished, such as the deep water stocks, which historically produced significant amounts of MOP.
- Catch rates of MOP on the currently fished grounds are quite high, around 60% of "culture" shell catch rate.
- Catch rates of MOP are 4-5 times greater on unfished grounds, compared to fished grounds
- MOP abundance is much less in areas north of Broome, such as the Lacepedes, compared to south (80 Mile Beach).
- Recruitment is greatest in shallowest water, where density of MOP is lowest. Conversely, MOP abundance is greatest at deeper depths, where recruitment is lower. Preliminary oceanographic modelling results suggest shallow water broodstock source for most of the spat settlement.
- Shell quality (as indexed by *Cliona* sp. infection rate) was higher in oysters from locations north of Broome (principally Lacepede islands), than locations south, although it was also strongly correlated with size, and average size was larger north of Broome.

4.10.1 The effect of growth and mortality on MOP harvest

The minimum estimate of standing stock of MOP was 1,450,000 oysters, while a maximum estimate was 2,740,000 oysters, using equation 6 (see methods [3.7.1] for further explanation of the figures). These estimates were used to examine potential MOP harvest based on the balance of recruitment (growth) and mortality (Figure 33).

A poor recruitment year with a natural mortality of 0.1, and assuming no unfished stocks (minimum), resulted in 53,000 MOP being available for harvest in a year (Figure 33c). Alternatively, a good recruitment year, with a natural mortality of 0.1, and assuming additional unfished stocks covering 30% the area of currently fished stocks (maximum), resulted in 711,000 MOP being available for harvest (Figure 33a).

These estimates are based on maintaining current stock levels of MOP and do not assume any likely benefits (e.g. increased growth and recruitment) from density-dependent effects of reducing accumulated stock of MOP. Furthermore, they are calculated on standing stock estimates from stock surveys in 2001, and would need to be upgraded on a regular basis (every 3 years) to ensure they remain relevant.

4.10.2 Preliminary harvest protocols

Our analyses indicate a substantial stock of MOP exists and could be harvested at a sustainable level. They lead to the following conclusion regarding sustainable harvest of MOP.

- Harvest of MOP should be restricted to the 80 Mile Beach area. North of Broome the stocks are less abundant, more infected with *Cliona*, and recruitment less regular.
- A legal minimum size for MOP needs to be set to separate it from the presently fished "culture" stock, and provide appropriate parameters for stock assessment. This may require a maximum size limit for 'culture' shell, and depending on the mode of MOP fishing, a maximum size-limit may also be required for MOP shell.
- Preliminary evidence from recent oceanographic modelling suggests that broodstock sources are in shallow water grounds North East of the main fishing grounds. MOP in these source areas will need to be adequately protected.
- Until the location of sources is more fully resolved, a cautions and conservative approach to harvesting is warranted.
- We recommend an iterative approach to harvesting MOP that is flexible and encapsulates changes in our knowledge of the biology of the oyster and dynamics of the population.

The following process to harvesting MOP is recommended:

1. Assume that MOP in the currently fished grounds (including Compass Rose) represent 100% of the available MOP stocks. The estimate of standing stock of MOP for this area is 1,450,000 animals.
2. Assume a natural mortality (M) of 0.1 on a poor recruitment year (Figure 33b).
3. This leads to a potential available harvest of 53 000 shell (For a minimum size of 175+mm DVM).
4. Accounting for recent data suggesting shallow waters as the principal source of broodstock, restrict the take on the inshore grounds to 30,000 MOP. The remaining 23,000 shell to be taken from Compass Rose.
5. Review the MOP TAC at 3 yr periods, contingent upon updated data from stock surveys and other relevant biological information, e.g. improved estimates of spatial area of commercially harvestable *P. maxima* habitat, knowledge of source-sink dynamics, improved size-fecundity and mortality estimates, spat settlement and recruitment data.

This harvesting protocol is designed to maintain the stock of MOP at its current level and represents a conservative approach to management of the stocks. However it is not unreasonable to speculate that a sustainable annual TAC for MOP may be higher than the figure presented above.

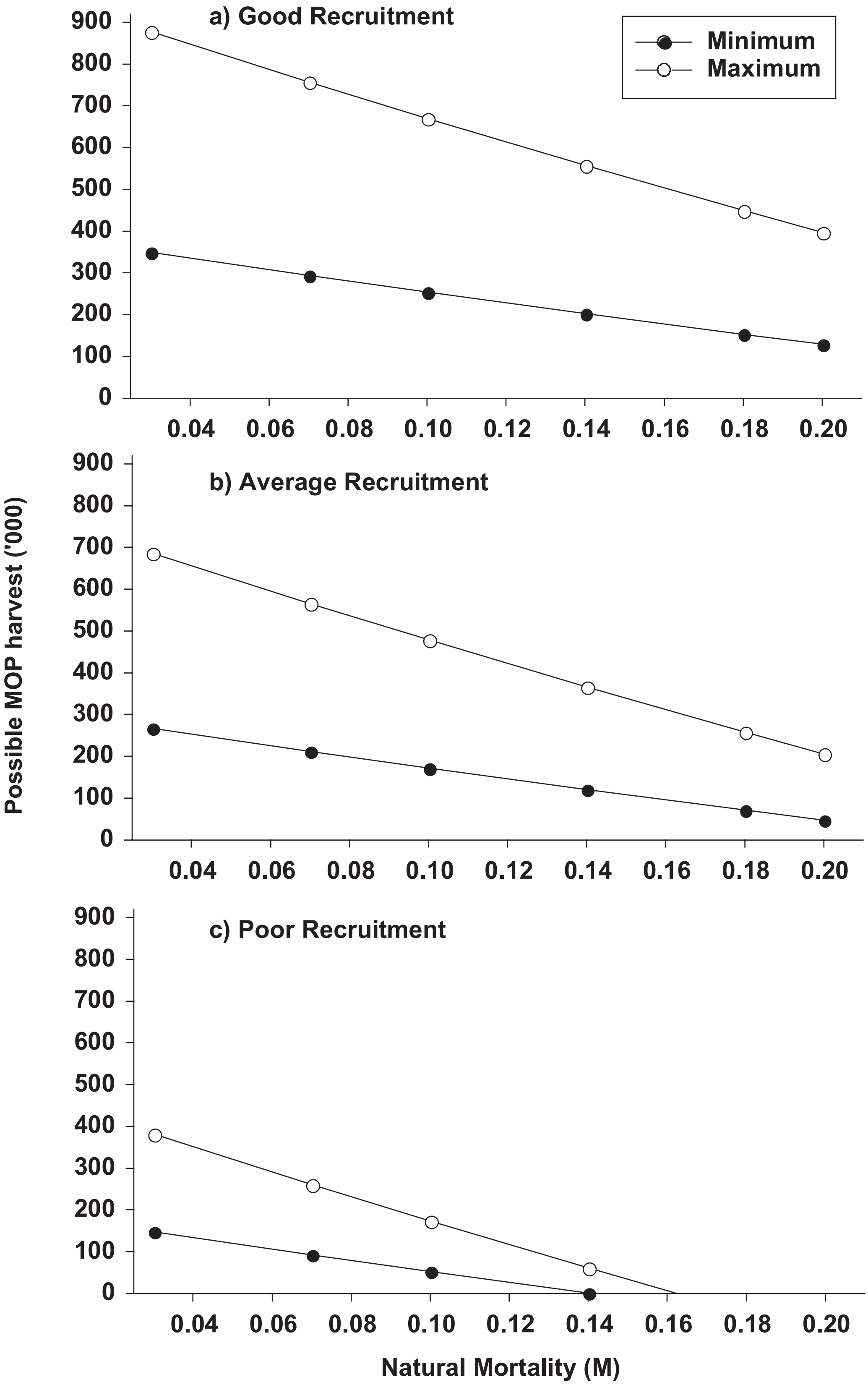


Figure 33. Potential 'surplus' MOP available for harvest, as a function of recruitment (good, average, poor) and natural mortality (0.02-0.2). Estimates from equations 6, 7, and methods in section 3.7. Minimum assumes no unfished stock; Maximum assumes unfished stock of 30% area of fished stock.

5.0 Benefits

One of the major outcomes from this project was a synthesis of existing data with new research on stock dynamics and environmental factors in order to develop a suitable harvesting protocol for MOP stocks. The benefits of this is to the pearling industry and WA community at large are substantial, as there is now a solid baseline of research data against which to evaluate any proposals. Should a harvest of MOP, for shell nacre, nuclei, or whatever other purpose, be commenced, a direct economic benefit to the community will ensue.

6.0 Further Development

This project has determined MOP stock status, whether harvesting could be sustainable, and in what areas it could be harvested from. A number of other activities needed to complete this process including:

- Improved estimates of spatial area and distribution of pearl fishing grounds.
- Further research on oceanographic and habitat factors that influence stock and recruitment relationships in the pearl stocks.
- Legislative considerations on how harvesting of MOP might be controlled in the Pearling Act.
- Economic research on the costs/benefits of harvesting MOP for a particular purpose, such as nacre production or nuclei manufacturing.

7.0 Planned Outcomes

The planned outcomes for this project were identified as performance indicators in the original project. Each of these will be addressed.

1. Size-fecundity relationships from two locations.

   Estimates were only obtained from one location (Exmouth Gulf). Estimates from 80 Mile Beach were not obtained because the timing of our sampling trip (October 1998) did not coincide with gonad maturation. This lack of a second sample was substituted by examining size-fecundity of preserved samples by a different technique (section 3.2.3).

2. Estimates of natural mortality from two locations are produced

   These were obtained using 2 different methods from 4 locations (Lacepede Islands, 80 Mile Beach Deep, 80 Mile Beach Shallow, Exmouth Gulf.

3. Growth curves for MOP from 2 locations are produced.

   Growth curves for MOP were produced for three locations (Lacepede Islands, 80 Mile Beach, Exmouth Gulf).

4. A reference chart for MOP stocks with respect to abundance and quality of shell is produced.

   Detailed descriptions of stock distribution and abundance, and quality of shell by spatial location and depth were provided.

5. Assessment of the potential for improving growth rates and quality by transplanting to quality sites is undertaken.

This planned outcome related to objective 4 of the initial project. This objective was replaced with a review of methods for establishing source-sink relationships in the pearl oyster stocks, which was achieved (see section 4.9)

All these project outputs contributed towards achievement of the final planned outcome, namely of developing a protocol for MOP quota setting based on an understanding on stock-recruitment relationships in the pearl stocks. Section 4.10 describes the specific relevance of each of these to the planned outcomes.

8.0 Conclusion

The project was successful in assessing the status of MOP stocks and developing a protocol for future harvesting based on knowledge of the biology and stock-recruitment relationships. It identified a number of fishery and biological issues relevant to any future proposals to harvest MOP.

- The fishery has been commercially fished since the 1890's and historical catches of MOP were substantial, peaking at 2000 tonnes in 1917.
- There has been a total ban on harvest to MOP since the mid-1980's, and most stocks have not been fished for over 20 years.
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- Preliminary evidence from recent oceanographic modelling suggests that broodstock sources are in shallow water grounds North East of the main fishing grounds. MOP in these source areas will need to be adequately protected.
- Until the location of sources is more fully resolved, a cautions and conservative approach to harvesting is warranted.
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10.0 Appendices

Appendix 1: Intellectual Property

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

Appendix 2: Staff

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