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FINAL REPORT FOR FRDC 91/3

KEY FACTORS WHICH AFFECT PRAWN RECRUITMENT AND IMPLICATIONS TO HARVESTING PRAWN STOCKS

N CARRICK

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1. EXECUTIVE SUMMARY

The project investigated factors believed to have influence on prawn recruitment to Spencer Gulf prawn grounds, and the implications to management. The project undertook study of the following:

- Prawn reproductive dynamics
- Larval biology
- Settlement patterns to nurseries
- The population biology of juveniles in nurseries
- Recruitment patterns to the fishery
- The effects of fishing on spatial distribution, spawner recruit relationships and factors influencing effective fishing effort.

Harvest strategies which would minimise the likelihood of recruitment decline and maintain "stable" economic return to the fishery have been addressed, however, further work in that area is required in conjunction with industry. A number of research results are of significance:

1.1 Population biology of *P. latisulcatus* in Spencer Gulf

Spawning occurs between November and March, with two peaks - one in mid December and another in early to mid February, depending on geographical location and water temperature. The relationship between size of female prawns and maturity is not typical to that documented in literature. Maturity increases from 0 to 20 % from 25 - 33 mm CL, respectively, with the amount further increasing from 20-30 % from 42-48 mm CL and decreasing thereafter with larger size. Therefore, "viable" spawners are expected to be those from 42-50 mm CL and further work in this area is being completed. The results indicate that < 5% of 26 mm CL prawns would be reproductively mature in January, suggesting relatively low population fecundity of the February recruits. It is expected that the June recruits to grounds and the 1+ year classes would contribute most egg production. It is hypothesised that larger prawns spawn twice over the annual breeding season.

The region has only two Penaeid larvae which occur in large numbers, ie. ***Penaeus latisulcatus*** and ***Metapenaeopsis sp.*** with both species having similar seasonal patterns in abundance. The study has shown that there can be large differences in *P. latisulcatus* larval populations between years, with numbers in 1992/93 having about 168 % more larvae than 1993/94. The difference in larval numbers was mirrored by a decline (approx. 154 %) in settlement to nurseries from 1992/1993 to 1993/1994. Owing to the fast growth rate over the summer-autumn period and pulses in settlement, the juvenile cohorts could not be separated over that period despite sampling over fortnightly intervals. Results showed that juvenile decay (mortality + emmigration) from February to May/June was substantial (> 0.3 month $^{-1}$). However, natural mortality of the closed population of over wintered juveniles from June/July to November was relatively low. Compared to the literature, the mortality of overwintered recruits approximates -0.05month $^{-1}$ and significant differences in annual survival of overwintered recruits were apparent. Most importantly, there was a significant relationship between initial numbers of juveniles and mortality, suggesting that density dependant control occurs in nurseries. Therefore, survival in nurseries would have a large influence on recruitment patterns to the fishery, especially for the overwintered prawns which recruit to the grounds in February and contribute most to the stock in northern Spencer Gulf.

Mortality of larvae were estimated at -0.266 and -0.062 day $^{-1}$ for zoea to mysis, respectively. Survival was estimated at an overall rate of 20% per day, which is consistent with the literature. Therefore, small changes in larval survival or increased length of larval life due to colder water temperature would have a large effect on settlement. Two peaks in the numbers of early larvae (zoea 1 and 2) were apparent, thereby corroborating a hypothesis for two peaks in spawning. Strong geographical differences in larval numbers occurred over time with the second peak in larval numbers occurring later in the south than in the north, suggesting that spawning occurs later in the south where water temperatures are colder. The northern part of Spencer Gulf has substantially higher densities of larvae than the south over the period November to January which may be a result of the combined effect of larval advection and larger egg production.

Oceonagraphic modelling in Spencer Gulf, as applied to prawn larvae, has shown a general trend for a net northern advection over the period November to January, whereas from February to April advection is believed to be in a southerly direction which would result in substantial wastage of larvae because of transportation in the opposite direction of the main nurseries. Therefore, the northern waters and intertidal regions of Spencer Gulf (ie. from 34 ° South) are important habitats for Western King prawn larvae and juveniles. Further industrial development and effluent discharge in Spencer Gulf by developers should consider both the temporal patterns and locations of high density areas of larvae and juveniles.

Settlement and juvenile densities are higher on the western side of the Gulf than on the eastern side, numbers generally increasing linearly with decreasing latitude on the eastern side. On the western side of the gulf, however, numbers do not increase linearly with decreasing latitude. Relatively high densities of settlers (and juveniles) occurred in the mid-Gulf region as well as in the north on the western side, with lower numbers in between. Patterns in juvenile numbers are expected to be the result of a combination of factors including: spatial egg production, advection and some unknown factor associated with a preference for habitat in settlement. Juvenile distribution is restricted to the intertidal zone with a general trend for higher densities in the mid shore region. The results have shown that there is a trend for the size of juveniles to increase from the mid to offshore intertidal zones and therefore sampling plans for estimation of abundance and survival should always incorporate stratified sampling which has proven to provide reasonable estimates of survival. Temporal settlement patterns have been shown to have large effect on recruitment to grounds, and to have an influence on fishing strategies. In some years recruitment to nurseries from January to February may be low, resulting in small recruitment to grounds in the April to June period. A low recruitment to grounds from April to June, results in a larger overall size of the population on trawl grounds and these patterns show inter-annual variability.

Hence, settlement and recruitment patterns to the grounds have a large influence on harvesting strategies in the period April to November which targets the capture of prawns > 60 % within and larger than the 16/20 per kg. head-on count.

A large recruitment to grounds in February results in high catch rates in the north from late April to June, but this is also dependent on spatial restrictions on the fleet to "control" depletion. Main nurseries within Spencer Gulf have been identified and these are situated north of 33° 40.00 South. The study found that low settlement at a nursery site visually affected by an oil spill had significantly lower recruitment compared to controls. However, the effect was believed to have been confounded by a natural climatic event which resulted in a substantial outbreak of blue green algae (cyano-bacteria). The importance of long time series of sampling juveniles (especially before an environmental impact) has been clearly demonstrated to industry.

1.2 Fishery aspects and management implications

A significant spawner recruit relationship was found using a decade of trawl survey data and this was of exponential form (Recruits = A+R**Spawners). However, further work on this aspect and the reproductive biology will be addressed, relating to the management of the Spencer Gulf prawn fishery. Trends in recruitment were also found to be associated with air temperature at Whyalla which have been shown to mirror temperatures in shallow water nurseries. Preliminary results indicate that the number of spawners > 42 mm CL has a larger influence on recruitment than temperature. An important implication from the work is that if spawner levels drop to low levels by fishing in association with a decline in temperature (or some adverse "weather" effect) then recruitment will decline. The latter implies that management must be adaptive and respond to changes in real time in order to "maintain" or rehabilitate the fishery from recruitment decline. Generally, it appears that for a level of 90 spawners (> 42 mm CL) per nautical mile, the recruitment is approximately constant. Below 85 spawners, the recruitment is largely affected. A reduction to 75 spawners would result in about a 20 % gain in yield but an expected decline of about 80 % in recruitment. Clearly, there needs to be controls on exploitation, with frequent real time feedback. It is pointed out that it is the spatial direction/effective effort over different periods which has large effect on depletion, rather than effective effort per se. Generally, exploitation should be "controlled" when spawner levels fall below 80 spawners . However, this aspect is being addressed in conjunction with industry using trawl sampling and log book and prawn size data.

It is evident that harvest strategies must be adaptive, responsive to changes, and based on real time due to the high potential for depletion by the fleet. For example high recruitment would result in management recommending higher exploitation and vice versa. Such adaptive control practices have been a hallmark of the management of Spencer Gulf prawn fishery, in conjunction with Industry. For stock maintenance, there is a need to minimise the capture of small prawns and to have different target sizes (spatial and temporal) to maintain profitability. The fishery cannot be managed as a global system because it is not stationary and there are can be differences in the mix of sizes between regions.

The results of the work outline the problems associated with calibration or standardisation of effective effort over time series. It has been shown that skipper skill has large effect on fishing power. Of the physical attributes, only engine horsepower and board size have a positive and significant effect on fishing power with small to large units. However, for larger units (>300 c bhp and 18 metres vessel length) there is no relationship between fishing power and vessel physical attributes. Owing to problems with data reliability, the lack of parameters (eg. vessel mass, boardsize) and the effect of skipper skill and motivation, it would appear that calibration of effective effort over time series using derived relationships would provide misleading information about the stock. Therefore, an independent method for stock assessment is required which should be compared to logbook data. One such method is trawl survey assessment, providing additional information which can be used directly for management.

Spatial statistics linked to a GIS and used in conjunction with conventional statistical methods (Anova, Ancova and glm) have proved to be a useful tool for the understanding of complex spatial patterns and parameter estimations. The depletion exerted by the fleet was shown to be high owing to prawn distribution and the behaviour of fishermen. Fishing is not a random process and the use of cpue for stock assessment without weighting for spatial differences (area/ patchiness) would certainly result in misleading stock assessment results. Intense fishing on large aggregations has been shown to reduce the population potential to spread or disperse and this may be a critical factor for stock maintenance if some spatial units are most important for stock maintenance. Owing to the complexity and need for further work over a longer time series, the value of different spatial units for stock maintenance will be addressed elsewhere.

A manipulation of the fleet was undertaken with industry to separate the confounding effects of fishing mortality and natural mortality. Of most importance, it has been demonstrated that natural mortality varies with season, sex and by size (age). Generally, adult *P. latisulcatus* have low natural mortality (-0.12 to -0.07 month^{-1}) compared to those documented in the literature, which corresponds to the relatively long life span of the species (ie. approximately 3-4 years from recruitment to grounds). Simple harvest models were developed using real time abundance and size data which showed the effect of mortalities (F, M), seasonal catchability, and price structure, on egg production and return ($/hr trawled). The combined effect of normal and delayed spawning and different levels of exploitation on egg production clearly suggested that premature fishing at high exploitation levels results in substantial reproductive loss, with marginal-to-no gain in financial return. The work on harvesting strategies is being enhanced using improved data input (eg. reproductive biology), SRR and models incorporating both spatial and global approaches for real time stock assessment and management of the fishery.

The FRDC project has been of significant benefit to industry, with information already being used in the management of the fishery. The sampling methods and analyses used will be improved with further work, thereby enabling better methods for stock assessment utilising spatial trawl sampling, logbook and prawn size, and sampling of juvenile populations.

2. INTRODUCTION

Penaeid prawn fisheries in South Australia are monospecific and based on the Western King prawn (*Penaeus latisculcatus*). The fisheries are unusual, in that they are situated at the southern range of the species distribution and are classified as Gulf-type (Spencer Gulf), Oceanic (West coast) and mixed (Gulf St Vincent fishery), see Figure 1. The Spencer Gulf prawn fishery is the largest *P. latisculcatus* fishery in the world, is centred at 34° 40° South, and is limited entry with 39 operators. Historical background to the fishery and applied aspects of research and management can be found in Carrick (1982), Stevens (1985) and Carrick (1988). The effect of trawling on selected fish and blue crab (*Portunas pelagicus*) has been addressed by survey assessment and experimentation, Carrick (1992) and Carrick (unpublished).

The by-catch species composition in the Spencer Gulf fishery has relatively low species richness with high prawn:bycatch ratios (eg. >10:1) compared to those Penaeid fisheries documented by FAO. This was expected as most studies were situated in tropical to sub-tropical regions, Alverson et. al (1994).

Trawl sampling, logbook data and commercial sampling of size of catch, provide important tools used to develop real time harvest strategies for different spatial units of the stock in Spencer Gulf (SPG). Management of the Spencer Gulf fishery is adaptive and responds to changes in spatial size distribution, exploitation and stock size.

Log book data is used as a tool for stock assessment in many fisheries to monitor historical trends. The results of the study on fishing power have shown that skipper skill is likely to have a major influence on the power of individual units, therefore, it would be difficult to adjust for effective effort of long historical time series because skipper skill and motivation cannot be quantified. Hence, an independent method for stock assessment over long time series should be a major goal of management. In regard to the latter, survey sampling is one method which provides additional data that can be used directly by management and integrated into fundamental research investigations, (eg. reproductive dynamics, juvenile population dynamics).

The management objectives for the Spencer Gulf fishery are focused in five areas:

1. ***Maintain the stock and minimise the risk of recruitment decline due to over fishing by spatial and temporal controls on exploitation .***

2. ***Minimise growth over fishing and maintain target size distribution by directing the fleet to optimal areas and fishing periods.***

3. ***Maintain profitability by increasing/maintaining the value of catch and reducing costs of fishing***

4. ***Ensure that methods and data used for stock assessment and management are reliable and accurate.***

5. ***Minimise bycatch and trawl impact by development of improved gear and harvest methods.***

The life span of *P. latisculcatus* has been shown to exceed 3 years from recruitment to grounds depending on the level of exploitation, Carrick and Correll (1989) and Carrick & Correll (unpublished). Growth rate is strongly seasonal with maximum growth occurring in autumn, see Figure 2. Owing to the long lifespan it was expected that natural mortality would be low. Subsequent studies (contained herein) have shown that relatively low mortality occurs over the first year class recruited to the fishery and mortality varies with season, sex and size (age). Research in Spencer Gulf indicates that spawning is mainly limited to the period from October to March with two peaks in recruitment to grounds (February and May/June) which is consistent with two annual settlement peaks observed in nurseries. Large annual differences in the onset of maturation and "delayed" spawning have occurred in Spencer Gulf (personal observation).

In the past, the combined effect of spatial depletion of key reproductive units in the stock and delayed spawning may have affected recruitment patterns, as a significant relationship between spawners and recruits is apparent in the Spencer Gulf prawn fishery. It has been estimated that approximately a 24% increase in fishing power of the fleet occurred from 1980 to 1994 due to upgrading of vessels and increase in horsepower. However, further work is being undertaken to obtain more reliable estimates of fishing power trends. Management should be adaptive and control effort in response to changes in recruitment and stock, in realisation that about 80 days of current effort would be a level which would substantially reduce the chance of recruitment decline due to overfishing. However, when stock is high more than 80 days could be applied, and substantially less when recruitment is low. A problem of using cpue logbook data in real time assessment of sustainable catch and effort levels is that there is insufficient lead time to set or determine the levels because of the potentially high (and variable) exploitation rates exerted by the fleet. Therefore, the fishery requires monitoring in real time, using a number of tools (see below).

Factors believed to effect recruitment to nurseries in Spencer Gulf are spatial egg production and reproductive viability, timing of spawning, larval advection and dispersal, and survival in the plankton. Factors associated with structuring recruitment to the fishery are settlement pattern to nurseries, growth and survival of juveniles and sub adults. Evaluation of environmental time series events (temperature, wind patterns, Enso sea levels) and the effects of fishing on recruitment is a major objective of research in Spencer Gulf and the West Coast fisheries. While recruitment has been shown to be associated with climatic events, it may also have association with fishing patterns.

Stock decline in Spencer Gulf in 1987 was associated with weather and exploitation patterns, while a recent "catastrophic" decline in the oceanic West Coast fishery was linked to strong environmental forcing. The West Coast fishery recovered from recruitment failure after two years of closure, which clearly indicates the resilience of Penaeid stocks to strong environmental disturbance even when spawners are reduced to exceedingly low levels, Carrick (unpublished). The West coast fishery is an oceanic fishery and, by nature, similar to a number of the "pocket" Eastern king (*Penaeus plebejus*) prawn fisheries with adults spawning offshore in oceanic water and recruitment to estuarine nurseries dependent on favourable larval advection for supply.

Apart from direct reproductive depletion over wider spatial units, the effects of fishing in Spencer Gulf may be more subtle than realised in the past. Intense fishing affects the potential for adult dispersal (ie. spread) and homogenises an otherwise heterogeneous system. Some spatial units may be more important than others for viable egg production and supply to nurseries. **If the latter is the case, the relationship between spawners and recruits may be redundant when based on a global system.**

The work addresses some of the issues detailed above and simple harvest models are outlined which draw in applied and fundamental studies. There is a close nexus between the population biology and management. Long-term management focused on sustainability requires an understanding of both applied and fundamental aspects of the species population biology, and dynamic processes associated with fishing. Most importantly, effective research and management requires high level cooperation with industry.

Garcia and Le Reste (1981), Garcia (1977, 1985, 1988) provide excellent accounts of Penaeid life history and population dynamics. The work of Penn and Caputi, (1985, 1986), Caputi, (1993) and Penn et. al (1995) has addressed spawner recruit relationships in Western Australian prawn fisheries and provides evidence that recruitment overfishing has occurred in at least two Penaeid fisheries. Cases of substantial stock decline due to intense overfishing in Pandalid shrimps which have longer life span (10-15 years) are known, but few have been documented, B Baxter (personal communication). A recent study by Wang and Die (in press) of spawner recruit relationships (SRR) and equilibrium yield in the Gulf of Carpentaria tiger prawn (*P. esculentus*) fishery, concluded that ***the present effort level will lead to decreased recruitment and stock size... fishing effort is excessive. It is therefore necessary to urgently consider new management options to control the likely increases in fishing effort in the tiger prawn fishery and to further protect the spawning stock.***

Since 1981 the Spencer Gulf fishery has been managed on the basis that there is a spawner recruit relationship, see Carrick (1982). Justification for the assumption and a conservative management regime was based on practical and theoretical grounds, R. May (personal communication).

Management adapted a conservative approach and subsequent study of life history and time series of fishery and environmental data in the Spencer Gulf has demonstrated that the management policy adapted from 1982 was credible. That is, a significant spawner recruitment relationship (SRR) has been determined from the study and management has been adaptive in controlling spatial exploitation by "learning" and applied research.

Quantification of the increase in real or effective effort, and the effect of high exploitation on the viable spawning population, needs to be addressed by many fisheries, including Spencer Gulf. It is difficult to estimate effective effort because some important influences (eg. skipper skill, motivation and learning) cannot be quantified. Moreover, data on many historical attributes (net spread, engine bhp, mesh size etc) and prawn catch, size and effort records in most Australian prawn fisheries are not reliable over the long term. Evidence for the latter is supported by skippers who had extensive experience in a number of major prawn fisheries (K Tiddswell, S Woods, K Nichols, D Workman, among others (personal communication).

A number of sections in the study are of interest. The work on fishing power, Geographical Systems (GIS) for spatial density profiles and estimation of the effects of fishing using trawl sampling to separate the confounding effects of fishing, natural mortality and real time management, has gained international interest (C Walters, D Fournier, personal communication). The work on spawner recruit relationships, although a preliminary study, is the first for a Penaeid fishery using a reasonable time series of assessments by a trawl sampling plan which considers spatial variation over wide scale.

The FRDC study has enabled vital life history information to be obtained and used directly in stock assessment and management. The study will assist in the refinement of sampling methodology and management.

Further model development will be undertaken by the author with collaborators which addresses sustainability of the resource in terms of spatial and global unit(s). Figure 3 illustrates the basic life history of Penaeid prawns where adults spawn in deeper waters, then larvae are dispersed, postlarvae settle in inshore nurseries and subsequently recruit to grounds. A flow diagram of important life history phases is illustrated in Figure 4. The study is focused to early life history, as well as recruitment to the fishery, fishery dynamics, and management of the fishery.

3. PRODUCTION, SPATIAL PATTERN AND FISHING POWER

3.1 Background

Fishing effort in a fleet increases over time due to increase in skipper skill, adaptation of fleet fishing techniques, (eg. U-turns on concentrations), improvements in gear and technological innovations such as radio networks, radar, Global Positioning Systems and Plotters etc). Therefore, the real effort termed "effective effort" of individual units needs to be standardised by increase in performance. Fishing effort is a function of hours trawled and the individual fishing power of vessels in the fleet. Generally, fishing power is described as the relative performance in catching. Excellent explanations of fishing power and case histories of standardisation of fishing effort are documented in Gulland (1956,1968), Beverton and Holt (1957), de Boer (1975), de Boer and de Veen (1975), Houghton (1977), Hovart and Michielsen(1975), Laurec (1977), Zijlstra and de Veen (1963), Rothschild (1972), and Fridman (1986). The studies by Griffin et. al (1977) and Brunenmeister (1982) are of most relevance as they relate to shrimp fisheries. Generally, in heterogeneous fleets of trawlers, fishing power has been shown to be proportional to engine power, vessel length, vessel tonnage and gear type. Moreover, skipper skill and learning have, in many cases, been advocated as a further, yet unquantifiable, factor influencing fishing power and the effective effort exerted in a fishery.

The study of fishing power is considered to be most relevant to the FRDC study. It was undertaken in an attempt to standardise fishing effort, to estimate cpue trends in the fishery and to determine annual effort which would reduce the risk of recruitment decline due to fishing. A further objective was to correlate changes in cpue with historical weather patterns (eg. temperature and winds), see Section 4. However, it was clearly apparent in the course of the investigation that early historical records on gear and vessel physical attributes were unknown, and for a number of units the records were unreliable. Therefore, estimation of effective effort, changes in abundance and exploitation over the complete history of the Spencer Gulf fishery would result in misleading information. Byrne (1978) and Sluczanowski (1980) examined the fishing power of the Spencer Gulf fleet on a global basis from 1968 to 1978, and did not consider the biases due to a different target size within the fleet and those due to location, among others. Byrne (1978) found that vessel length, horsepower, headline length and gear type (double versus single) had significant effect on fishing power. However, when a subset of the data restricting vessels to double rig was used (1975-1979), it was found that only vessel horsepower and headline length had significant effect on power, Carrick (unpublished). It was concluded that further work should be undertaken using more reliable data, which would require cooperation with industry and it was suggested that skipper skill has a major influence on fishing power, Carrick (unpublished). Sluczanowski (1980) examined the relationship between fishing power and vessel length, engine horsepower and number of crew, and found that only horsepower had a significant effect, which was best explained by square root bhp.

The work of Robson (1966), Stark (1972), Searle et. al (1981) and Brunenmeister (1982) are most relevant to the development and application of analytical methods for study of complex interactions involving estimation of fishing power and effort standardisation in fishing fleets. Few studies have documented fishing power increase because data are either unreliable or limited (ie. unknown physical characteristics of individual units). The FRDC work in Spencer Gulf is unique because a range of reliable information was validated and some parameters (eg. mass) were directly estimated from ship survey records and vessel plans (eg. displacement statistics) by the author, with assistance of the Department of Marine and Harbours and Industry.

3.2 Objectives

The objectives of the study were:

(a) To outline trends in production, nominal effort and nCPUE

(b) To determine factors which affect fishing power and determine current levels of effective effort in the fishery

(c) To determine abundance trends using standardised CPUE and correlate recruitment estimates and weather patterns

(d) To outline general harvesting patterns in the fishery

(e) To investigate prawn catch and density profiles and examine the effects of fishing.

3.3 Methods and results

Fishers daily and monthly logbook data were validated and manipulated using a database system developed in FOCUS. The blocks detailed on charts were digitized and data transferred to a geographical information system (GIS) using ARC/INFO and data subjected to an inverse differencing interpolation technique using SURFER. During April and May over 1987, 1988, 1989 and 1990 field monitoring of the fleet fishing in "close quarters" was undertaken in areas of initially high concentrations for studies of fishing power. Analytical methods used to estimate the relative fishing power of vessels included Robson's method of fitting constants, Steele and Torrie (1972), Robson (1966), Carrick and Correll (unpublished). Logbook data from 1978 was used to estimate the relative increase in fishing power (fp) in 1987/88 to 1989/90. An extensive study of vessel physical attributes was undertaken using information from the Department of Marine and Harbours, individual fishers (survey and vessel plans) and information direct from logbooks (board size, engine BHP, vessel length, navigation equipment etc). For each vessel, information was validated and displacement mass calculated with the assistance of ship surveyors. Carrick (unpublished) provides a detail of factors expected to influence fishing power and input controls needed for the management of the Spencer Gulf fishery. The types of vessel physical attributes used in the investigation of fishing power have included:

- Vessel length (LOA)
- Vessel bhp (sqrtBHP)
- Vessel displacement, or the mass parameter (MASS) determined from survey tests and vessel plans
- Gross registered tonnage (GRT)
- Trawl board size (BSIZE)
- Propeller dimensions and pitch
- Kortz nozzle
- Draft, beam, waterline length
- Net type and spread
- Gear configuration (single, double, triple, quadruple nets)
- Global positioning systems (GPS)
- Hull design ratios

Logbook cpue (kg.hr) were restricted to fishing operations in the same area (Blocks 39/36, see below) within April/May over three years, 1988, 1989 and 1990, and the fishing power determined for 34 vessels. The effect of night on cpue was shown as highly significant ($p<0.001$) with larger effect than vessel. Subsequently, the effect of Night was removed by using it as a dummy covariate for each year, with adjustment to means. Vessels fished the same area, thereby eliminating the effect of location, with operations monitored at sea by the author. The number of sampling units was 1020 and cpue data were logged as the effect of boats was expected to be multiplicative, see Robson (1966). The relationship between log catch rate was compared between years, using simple regression and fishing power estimated using a standard vessel having the same vessel characteristics and skipper. Analysis and scatter plots of fishing power data showed that square root of bhp was a better fit in linear regression than number or log number.

Mean fishing power of each vessel over three years and for each year was estimated, and used in a multiple regression of the relationship between fishing power and LOA, GRT, MASS, sqrtBHP and trawl board size. A number of techniques were used to determine the effect of each variate including best sets, regression and "drop down" techniques using Genstat 5 and Minitab. Appendices 1-3.2 detail regressions on individual and important combined variates.

The following results from multiple regression of fishing power averaged over three years on variates are of main interest:

- Fishing power = 0.386 + 0.037 sqrtBHP + 0.001 MASS - 0.001 GRT - 0.013 LOA

- Fishing power = -0.480 + 0.033 sqrtBHP + 0.001 MASS - 0.002 GRT - 0.004 LOA + 0.32 BSIZE

- Fishing power = -0.317 + 0.034 sqrtBHP + 0.283 BSIZE - 0.011 LOA

- Regression of each variate alone indicated that only sqrtBHP and BSIZE had significant regression slopes, see Appendix 1. The horsepower slope was 0.029 ± 0.009 (t=3.31) and this only accounted for 23.2% of variance in the data, while the board size slope was 0.302 ± 0.101 (t=2.99) and explained 19.4% of the variance.

- Restricting the multiple regression to larger BHP and length resulted in a significant (t=2.69) negative co-efficient for GRT and all other variates were not significant. When board size was added (without restriction on size or engine power) both engine power and board size were significant ($p<0.05$). However, with restriction on size (>300 BHP and > 18.0 metres), the engine power was significant but board size not significant (t=1.71). GRT was significant in a negative direction (see Appendices 1-3).

- Regression of units with larger engine power (ie. >364 BHP) indicated that no variate was significant ($p>0.1$) with and without addition of board size.

The results are difficult to interpret, but it is suggested that skipper skill has large effect on fishing power which is supported by field observations and other studies. The analysis indicates that increase in vessel length from 19.8 to 22.0 metres would have no significant effect on fishing power, providing engine horsepower is restricted to 365. However, there could be a small increase in power by increase in mass, especially in rough sea conditions in some areas. Gross registered tonnage calculated as the relationship (vessel overall length*breadth*draft) *0.22119 is either an unreliable parameter or the vessel design ratios of some larger units results in less efficient trawlers (ie. beam/length). Vessel mass, as derived from displacement tests, is a more reliable estimator of size than GRT, and this is expected to be relevant to other Penaeid fisheries.

The fishing power estimates were used to recalibrate the 1976 power estimated from Sluczanowski (1980) to 1987-1990 units. The following results are relevant:

- The average fishing power in 1978 was 0.69, whereas the average from 1987-1990 was 0.86.

- There has been a steady increase in average fishing power from 1987/88 to 1989/90, with the average power estimated at 0.83, 0.86 and 0.90 for 1987/89 and 1989/90 respectively.

- The increases in average fishing power from 1976 to 1987/88, to 1988/89 and 1989/90, were 20.3%, 24.6% and 30.4% respectively.

- Considering engine power alone, the increase in power between 1976 and 1987/90 estimated from regression slopes was approximately 10%. That is, less than half of the increase in fishing power of the fleet from 1976 to 1987/90 is attributable to increase in average engine power of the fleet, (cf. 24.6%).

The fishing power from 1987/90 has been shown to be proportional to the square root of BHP of engine, but this alone explained 23% of the difference between boats. Appendix 2 details the relationship between fishing power and bhp, vessel length and board size over each year. It is evident that board size has significant effect on power, but, at best, the variates only account for about 32.6% of variance in data. It is suggested that skipper skill and motivation, an unquantifiable variable, has large effect on fishing power and consequently calibration of effective effort is not a trivial exercise.

Information from an investigation of net spread undertaken in collaboration with Frank Chopin and industry, was subjected to an ANOVA to test the effect of trawl board size and setting angle. Figure 5, Table 1 and detail results which show that larger board size has significant ($p<0.05$) effect on net spread over two angles of attack using the same net design. Net spread and engine power are important factors influencing catch rate and fishing power in a fleet.

Carrick (unpublished) experimentally tested different gear types in commercial operations (over a four month period) and found that a change from double gear to quadruple gear (with same headline length) has potential to increase fishing power by 47%. However, loss in trawl time occurred with 4 nets (termed "double-trouble") resulting in a net gain of 36% in efficiency, (unpublished). Therefore, there is potential for large increase in effective effort in the fishery if the fleet were to change to quadruple gear. A change in quad gear would need to be offset by a reduction in available fishing nights to maintain effective effort at current levels.

The effect of trawl board size on fishing power was found to be significant when the complete range of vessel size and bhp was examined. Analyses were undertaken with and without trawl board size, to determine the effect on fishing power. Moreover, analyses were restricted to vessels >than 300 engine horsepower and >18.0 metres, and to vessels with horsepower >364.

Logbook data were analysed for 23 vessels in 1986 using a similar method described above, and fishing power estimates compared to 1989/90. The analysis was undertaken to show the substantial influence of skipper skill and motivation on fishing power.

Spencer Gulf production, nominal effort and nominal catch rate (nCPUE) from 1968-1993 are illustrated in Figure 6. The level of production has remained relatively stable with a large improvement in size. The bulk of the catch is under the 17 whole prawn count, with a significant proportion in the under 15 per pound (head-on category). This represents a substantial improvement of prawn sizes from the mid 1970's and early 1980's, where substantial quantities of 20-30 and 30-40 and 40+ per pound (head-on) grades were captured (Carrick unpublished).

Decline in Spencer Gulf production occurred in 1986/87 which was directly reflected in low level recruitment indices obtained from trawl assessment surveys. Prawn production on the West coast is characterised by a strong cyclical trend with major stock declines in 1977 and 1992/93 followed by substantial recovery in 1995, (Carrick unpublished). It is noted that survey trawl assessment was used to gauge recovery and assist in management of the fishery, (see Figure 7).

Seasonal productions in Spencer Gulf from 1987/88 to 1994/95 are detailed in Figures 8 & 9. Harvesting is restricted to 6-7 periods of the year, with catch rates dependent on relative abundance and spatial structure (ie. aggregation). It is noted that, in recent times, the fleet fish for 65-75 days over each year with fishing trips (or fishing periods) being 7-16 days in duration with operations restricted to the new moon phase when catchability and quality are higher (personal observation). In contrast, prior to 1981 substantially larger numbers of days were spent fishing (greater than 200) resulting in excessive fishing costs and economically wasteful fishing practices due to large scale capture of smaller prawns (personal observation). It is evident that in a fishing trip of less than 15 days, the fleet can catch over 20-30% of the annual catch by a system developed in conjunction with industry which relies on survey sampling and adaptive re-sampling (termed spot surveys) for the development of harvesting strategies.

Fishing in Spencer Gulf is mainly targeted to the March-June period where >70 % of the catch is taken, and to the November-December period. The fishery is usually closed to fishing from late December to March, and from July to October, with closures over the full moon periods extending for 10-15 days depending on spatial stock size and the size of prawns.

Since 1984 there has been a substantial decrease in smaller prawn grades (ie. 31-40, 26-30 per pound head-on) due to management controls and industry cooperation in research and management. Knowledge gained about spatial and temporal patterns obtained from trawl assessment, logbook and tag data are directly used in the management process. It is noted that over 30% of annual catch is taken within 24-30 days and that high average catch rates (>250 kg.hr) occur in mid May when water temperatures are relatively low (<16° C).

Substantial value (and biomass) increase occurs by allowing prawns to grow over the period March to April when growth rate is at maximum level. This has major significance to the northern area of Spencer Gulf where main recruitment to grounds occurs in February of each year - whereas in the southern grounds, main recruitment occurs in May to June. Appendix 4.0 illustrates the differences in cohort structure and recruitment, with >recruitment occurring in June in the south, whereas substantially more recruitment occurs in February in the north (see Section 8, Figures 15 and 16). Premature harvesting from March to April in the northern area would result in substantial loss in potential value of harvestable stock.

A major problem is mixing of sizes and large pulse movements of smaller prawns into open grounds. Patterns have been identified over long time series using spatial data obtained from trawl surveys and monitoring the size of catch on daily basis. Different regions in Spencer Gulf are monitored to determine optimal harvest periods. Another point is that the costs of fishing have reduced by increase in efficiency and reduction of trawl hours through the cooperation of fishers in research and management.

A number of summary points relating to the fishing power and effective effort of the Spencer Gulf fleet are of relevance:

(a) From 1978 to 1989 there was an estimated 30% increase in fishing power, which may be under estimated. The recent (1991) adoption of GPS plotters by the fleet is likely to have resulted in further increase in fishing power (fp), especially in the southern area of the Gulf and at periods of intense fishing operations on denser aggregations (eg. 600 -900 kg.hr) in the northern area of Spencer Gulf.

(b) Relationships were examined using multiple regression with step-up and best-sets regression for tests of effects of single or combined attributes (bhp, length, mass, gross tonnage, board size), using an analyses which eliminated the effects of night and differences in abundance due to location. Logbook data from 1987/88 to 1989/90 included vessels ranging from small (15 metre) to large (22 metre) and bhp from 270 to 500. The regression of all five variates on fishing power only accounted for 44.7% of the variation between boats. Results indicated that a relationship between bhp, board size and vessel length was apparent, but only explained 40% of variation in data. Length considered alone had no significant effect on fishing power. Engine power and board size had significant relationship to fishing power. Nonlinear regressions of each variate were analysed, with bhp showing exponential response, whereby fp largely increases from 200-300 bhp and reaches a plateau or asymptote at around 360 bhp (see Figure 10). Combination effects were apparent, as smaller powered vessels usually towed smaller boards and, at those sizes, the vessels would not be expected to compete favourably with larger vessels during operations when tide is strong and gear under heavy load.

(c) Scatter plots of the fishing power on 5 varieties (see above) indicated that smaller (<18 metres and <300 engine bhp) vessels had large influence on regression relationships. Subsequently, analyses were restricted to vessels larger than, and equal to, 18 metres and larger than, or equal to, 300 bhp. The results indicated that no variate alone had a significant relationship with fishing power. However, mass showed a tendency for exponential response, indicating that fp increase diminished with increasing mass and reached an asymptote at around the 1994 length replacement maxima (19.4 metres). Only bhp, mass and board size had positive relationship to multiple regression, but only explained about 42% of variation in data. Length was shown to have no significant effect on fishing power, especially at sizes >18.0 metres. Bhp was the only variate showing significant relationship with fp. Board size increase (or area) had no effect on fp with larger units (above 18 metres and 300 bhp).

Over 10 physical factors contribute to increase in fishing power including: the adoption of stabilisers in the earlier years to more recent developments in communication, (eg. radio networks, sea phones, scramblers, facsimile, etc.) and GPS plotters. In the Spencer Gulf fleet bhp, gear configuration and skipper skill are considered to be major factors influencing fishing power. Indeed, attempts to standardise or adjust effort by fishing power have not been trivial.

Adjustment has proven difficult in the Spencer Gulf fishery, which has historically reliable logbook data compared to most Australian Penaeid fisheries. Albeit, the use of the standard indicator cpue (nominal or standardised) in stock assessment, as an abundance indicator over a fishery's history, should always be treated with caution on practical and theoretical grounds, because the real effort exerted by a unit tends to increase in time and is difficult to quantify "effective" change.

A number of functions were used to estimate fishing power and effective effort increase from 1980 to 1994. However, data on vessel mass were not complete over time series, and therefore could not be used. For simplicity, the increase in fishing power was based on the relationship between engine power, length and board size, and an expected fractional increase by learning. If engine power were used alone, the results may be misleading. Furthermore, it must be realised that additional analyses need to be undertaken using standard vessel(s) for a more reliable estimation of the increase in fishing power, (see above). Using the derived function, incorporating the three variates, plus allowing for an annual increase of 0.03* in fishing power, the relative fishing power and effective effort trends were estimated from 1980-1994. Preliminary estimates using physical parameters and learning indicate that approximately a 25-30% increase in the average fishing power of the fleet has occurred from 1980 to 1994. Over the same period, nominal effort was reduced from around 39,000 hours in 1980/81 to 25,600 hours in 1994/95. Preliminary results imply that the decrease in effective would be about 15% to 18%.

However, analysis indicates that the average fishing power of 23 units in 1986 was significantly larger ($P<0.05$) than in 1987-1990 which was associated with an expected higher level of skipper skill and motivation in 1986 (unpublished). *Therefore, attempts to calibrate fishing power (and effective effort) using physical parameters and/or to use an "expected" (eg. 2-3% per annum) learning increase, may result in misleading information and error in stock assessment. Further work is being undertaken in conjunction with industry, to address the complex issue of fishing power and effective effort trends in the fishery.*

The recent (1990/91) adoption of GPS by the fleet was not considered in the analysis and will be addressed in the future.

Production data from 1988/89 to 1993/94 obtained from daily logbook records (catch, trawl hours, spatial fishing blocks) and monthly landing logs were validated and subjected to surface interpolation plots using longitude(x) and latitude (y) in decimal degrees and catch (z). Charts 777, 778 and 779 incorporating the irregular fishing blocks were digitised and data stored in ARC/INFO. Map files were transferred to SURFER for simple inverse distance squared interpolation of catch data from 1988 to 1993/94, (see Figure 11).

The distribution of catches over all years are from a relatively small area of the Gulf (< 15% area) and catch is patchy, with large annual peaks (> 500 tonnes) consistently occurring in an area termed "Middlebank" situated in the northern part of the gulf. However, in 1990/91 >250 tonnes was captured in the south western sector of the gulf. Fishing is not a uniform or random process as spatial catch reflect prawn abundance and behaviour (movement and aggregation), management strategies, management restrictions (optimal size, closures) and fleet behaviour. Over 60% of the catch is derived from two grounds which occupy less than 8% of the area of the Gulf, (see Figure 12). General patterns in spatial structure of catch are detailed and there is a need to refine the methodology using better interpolation, scaling and statistical techniques in order to show finer spatial patterns and seasonal differences within each year.

The database systems developed have the potential for integration into a Geographical Information System for detailed study of spatial recruitment pattern, size (contours), viable egg production, biomass, density profiles, abundance and value which can be used as background "overlays" for an electronic whiteboard with direct communication to operators (see Section 4).

4. THE EFFECTS OF FISHING ON DISPERSAL AND POPULATION FECUNDITY

4.1 Background

There are no studies in the literature which show the direct effect of trawling on spatial pattern (or dispersal) or on local egg production. Furthermore, fishing mortality and natural mortality estimates are usually based on modelling methods which are usually confounded and not independent. The most appropriate method to obtain reliable estimates of mortality parameters is by manipulation of the fleet requiring industry co-operation and support, (see Carrick 1982). The investigation is the first documented study in separating the effects of fishing (F) from natural mortality (M) using a manipulative field study based on trawl survey assessment (before, during, and after fishing) and utilisation of fishers' logbook data in determining local or smaller spatial effects of fishing. The study on depletion using logbook data and catch measuring appears unique in that both initial abundance, area and patchiness were considered in the study. No relevant studies were found in the literature for Penaeids and this is surprising because of the importance to management of understanding population dynamics. An earlier and somewhat "rough" or trial manipulative investigation of the benefit of a closure in Spencer Gulf resulted in long term economic gains to industry by refinement through understanding spatial change and prawn size composition, (Carrick 1982).

4.2 Objectives

The objectives were :

(a) to determine the effect of fishing on dispersal;

(b) to separate the effects of fishing mortality from natural mortality using a fleet manipulation and sampling;

(c) to determine seasonal differences in natural mortality;

(d) to determine the effect of fishing on local population patchiness;

(e) to determine depletion and compare the effect of initial abundance, area and patchiness on F and q;

(f) to compare density profiles of prawn numbers and potential egg production using GIS and to examine the effect of fishing on local populations;

(g) to outline the size composition over the northern grounds and shown dynamic changes in biomass and size attributable to recruitment, growth and mortalities.

4.3 Methods and results

Hallprint (SA) streamer tags, designed and tested by the author and M Hall, have been used as a direct management tool and for understanding processes associated with growth and movement. As noted above, seasonal growth pattern was modelled using mark recapture data and growth is based on a harmonic model which appears realistic over the captured commercial size range. Maximum growth rates occur over the February to May period. Tag recapture data (20,000) were subjected to plots using ARC/INFO and direct plots on charts in order to develop a generalised model of movement (unpublished). Figure 13 illustrates a general model of the main movement trends over fishing grounds. Results show there is a trend for southern movement of prawns in the northern grounds, while in the southern grounds movement has more spread but there is substantial movement in a north east direction to the Wallaroo grounds. Prawn movement patterns are not random and have strong directional patterns which will be addressed elsewhere. It is evident that intensive fishing (ie. high fishing mortality, F) on aggregations at important movement "pathways" would reduce adult movement or dispersal potential and reduce overall spread which may have effect on reproductive "viability". GIS systems were used to show density changes in northern Spencer Gulf which reflect a density profile in the region before and after fishing.

4.4 Results

(a) Separation of the Mortalities (M, F), eliminating q and change in Spatial Pattern.

A number of experiments and simulations were undertaken to determine the effects of fishing and natural mortality. The information detailed below was based on a study undertaken in 1988. The sampling plan consisted of dividing the northern region of Spencer gulf into 14 Blocks (7 fished versus 7 unfished) and sampling before and after fishing, (see Figure 14). Covariates (number of fishing days, water temperature) were included in the analysis to gauge the influence of effort (days) and temperature. The variance/mean ratio of sub sets of stations was estimated before and after fishing and used as an indicator of change in patchiness after intense fishing operations. Sampling took place in February and April (ie. before fishing) and May, June and November (after fishing) with different temporal sequences and amounts of fishing (days) in each treatment (fished versus unfished).

The assumptions relating to the tests were:

- The population was closed. Tagging was undertaken to test and validate the assumption. Results showed that no detectable movement took place between unfished and fished populations, or from outside of the study area. The effect of further recruitment to the grounds was removed by a method developed using MULTIFAN and FOCUS, (see below).
- That catchability (q) differences between periods had no effect on estimates because q was assumed constant between fished and unfished populations. The effect of area and initial abundance and temperature on q was examined using ANCOVA.
- Natural mortality rates were similar between fished and unfished populations implying that there are no density dependent effects and natural predation rates are similar. This assumption may be the main criticism.

Previous studies on catchability showed that there is no significant difference in vulnerability between April and early June and November over dark moon phase, Carrick and Correll (unpublished). The sampling study took place on same dark moon phase to minimise catchability differences attributable to both moon phase and tide. The difference in slopes between fished and unfished populations, therefore, is an estimate of the effect of fishing, as q is cancelled on the assumption of no difference within same periods over treatments. Ten standard sampling units (20 metre freezer trawlers) with the same towing capacity (3 knots) were used in the study. Vessels had same bhp and gear (ie. 2*7.5 metre Spencer Gulf gundry design and same board dimensions). Previous work has shown that there was no significant differences in catch rates between the survey vessels standardised on a unit distance of trawling or area swept. From each trawl station (1.8-2 nautical miles) a sample of between 300-400 prawns was blast frozen for subsequent measurement ashore by trained factory personnel, (ie. 90 stations). The biomass of catch was estimated using numbers of standard buckets and mean bucket weight from each net. The trawl time and trawl distance from forms were input into in a data base system using programs and procedures written in DATAFLEX and FOCUS. Prawn densities (number of prawns at 1 mm carapace length intervals) were standardised to a nautical mile and files downloaded for subsequent analysis using GENSTAT 5, MULTIFANand MINITAB.

Size frequency based on abundance for each station were input into MULTIFAN but this proved a difficult and time consuming task due to the number of samples (2 sex x 90) and file manipulation restrictions required for simultaneous analysis of cohort structure. For computational simplicity, weighted size frequency data from each station were pooled into subsets of blocks using the computational power of focus. MULTIFAN was used to determine cohort "cut-off" points between gaussian distributions, track cohorts and remove further recruiting classes. The "cut-off" points over each block and time period beginning April 1988 were used as a delimiter in FOCUS to determine densities of stations with new recruitment removed. Figures 15 & 16 illustrate changes in population structure and relative abundance over each sex from February to November for the fished versus unfished regions.

The effect of fishing is evident in May and the size distribution of prawns is larger in the fished area due to the harvest strategies adopted. Data used in the analysis were based on sampling from April (before fishing) to November, after 3 intense pulses of fishing.

It is evident that large spatial changes occur from February to April due to growth, recruitment, movement, and natural mortality. Mark recapture studies did not detect movement of the larger (older cohort) from the sampling region from February to April and therefore decay in prawn numbers and biomass is likely to be attributable to natural mortality with a rate exceeding 0.2 month, which contrasts with the relatively low M of the recruit class (see below). This result implies that M for large prawns increases with size and/or is highest in larger sizes at specific time periods (eg. February to April). High M values of larger prawns could occur after spawning, resulting in substantial impact on biomass and stock value. Figures 17a and 17b illustrate changes in prawn biomass at fished and unfished regions. Since all model simulations are sensitive to M, including egg production, eggs per recruit and value of stock, it is important that estimates of M for older (larger) cohorts are refined by survey sampling and catch monitoring. Statistical analyses of data were undertaken using grouped regression with procedures testing homogeneity of variance (Bartlet's test), parallelism, differences in slopes, and elevations of each sex. Table 2 provides estimates of instantaneous natural mortality and it is evident that mortality differs between season and sex. Generally, the natural mortality rates are higher in female than male prawns. Estimates of natural mortality were used in the development of harvest models (see Section 9).

(b) Depletion

Data on the size prawns in the commercial catch were monitored on a daily basis in the field in 1988 and 1990, and logbook information used to estimate number caught by day over different spatial units (or fishing blocks). The decay in prawn numbers and catch rate (kg. hr) were analysed using grouped linear and nonlinear regression. The study was designed to eliminate the effect of differences in catchability induced by moon, tide and water temperature.

Depletion scenarios over 1988 and 1990 took place at same areas over short time intervals (5 days) and effects of natural mortality are therefore regarded as small and similar between periods. Logbook data were manipulated using FOCUS, and effort standardised for each vessel using estimates obtained from a study of fishing power. A simple Leslie depletion model was applied with 30 units used in the study with every unit fishing in each day. All statistical procedures were written in GENSTAT.

The relationship between log cpue and day, over April 1988 and 1990, are detailed in Table 3 and illustrated in Figures 18a and 18b. The regression slopes of log number and log cpue were similar within Year and are significantly ($p< 0.05$) different between years. The instantaneous fishing mortality estimates (F) are high being 0.256 and 0.324 day in 1988 and 1990, respectively. The high mortality is due to targeting of high spatial aggregations in the vicinity of an area referred to as Middlebank.

An exponential regression was a good fit to the 1990 data as it explained 89 % of variance with the decay rate being 0.350 ± 0.044. However, for 1988 while the nonlinear regression provided a better fit than the linear model, the variance accounted for was small (59.2%) and the error large. *These results clearly show that the fleet exerts large effect on local subpopulations.* Regressions of cpue (number, kg.hr) on cumulated catch numbers and kg provided estimates of Leslie catchability estimates (q). The q values were 0.02 and 0.031 for 1988 and 1990 respectively. Linear regression accounted for 71.5% of variance in 1990 but only for 52.9% of the variation in the 1988 depletion. It was evident that extrapolation to the x-axis would result in a biased estimate of initial numbers and biomass. Other workers have reported similar problems associated with bias and estimation using Leslie and Delury models, Seber (1972) and Walters (personal communication).

The effect of initial abundance and area on q were estimated using each as a covariate in a generalised linear model (GLM). The general form of the model used was Y=AX(A); Covariate X where Y=cpue, A=Day and X=initial abundance, area and initial abundance and area.

Initial abundance (1 day before fishing) and final abundance in June of each year was obtained from survey and used to estimate Z. Area available to trawling over both years was obtained from GIS estimates. The advantage of direct field observations (including size sampling) over both periods and validation of logbook information assisted in understanding the effects of fishing.

Initial abundance was based on area swept using a spread factor of 0.75 derived from experimental tests undertaken in collaboration with R Bailey and F Choppin (see above).

The area available to fishing in 1988 was larger and mean abundance similar, but the degree of patchiness higher in 1990 as reflected by higher standard error in mean owing to high catch rates at three localities. The effect of area while decreasing the adjusted mean square in the GLM did not have significant effect on decay. However, when area was included with initial abundance both covariates were significant ($p<0.05$). With and without covariates the effect of Year was significant ($p<0.05$) with no significant Block interaction reflecting similar spatial sequences of serial depletion between years which was observed in the field.

Using day fished, the Z values translate to -0.133 and -0.152 for 1988 and 1990 respectively. Although area available to fishing tended to decrease decay in prawn numbers, it was not as strong as the effect of initial abundance or density. It is suggested that high aggregation and larger patchiness in 1990, combined with the fleet adapting GPS plotters, is likely to have contributed largely to the higher fishing mortality rate in 1990. The difference in F between 1988 and 1990 are substantial despite similar days of effort, initial abundance and area.

The results clearly indicate that most of the depletion occurs within 5 days and is reflected by high mortality rates (ie. 0.13 to 0.15 day, see above). The use of a fixed fishing mortality parameter in global modelling approaches appears unrealistic, because it cannot be constant or fixed in fishing operations which deplete patches of varied size. It should be obvious that spatial structure and fleet behaviour have large influence on fishing mortality and process modelling needs to incorporate spatial structure. Global modelling approaches appear unrealistic and irrelevant on both practical and theoretical grounds. The effect of fishing on spatial structure is detailed in Table 4, indicating that intensive fishing tends to homogenise pattern as reflected by reduced variance/mean ratios in the most intensively fished regions (see Region 1).

(c) *Effect of Fishing on Spatial Structure.*

Trawl sampling has shown that peak recruitment (males <32, females <34 mm CL) to the northern grounds occurs in February, with recruit density and population fecundity decreasing from north to south, see Figure 19. Tagging and trawl sampling has shown that prawns grow rapidly from February to April and disperse southwards. Low population fecundity in the southern part of study region over all years is mainly attributed to depletion, as effort is targeted to an area in the vicinity of stations 67-2 (Middlebank) in order to optimise harvest value (>70% LE 16 per pound head-on), see Figures 20a and 20b.

It is pointed out that different regions within the Northern area are closed to fishing from December to April/May with a number of regions remaining closed all year; hence the results reflect the patchiness of the population and the dynamic changes in spatial distribution unconfounded by the effect of fishing.

Inverse difference interpolation using SURFER was used to illustrate dynamic changes in spatial patterns in population fecundity and prawn numbers, using trawl sampling over a sampling grid (or block) in the northern area (main channel), see Figure 21. However, statistical analysis has shown that the interpolation model applied to data tends to force pattern and is misleading. This will be addressed elsewhere, however, it is noted that kriging has been shown to be a powerful tool for analysis of complex spatial data (see Section 4). Figures 21.2 to 23 illustrate changes in prawn numbers and population fecundity from February to June in 1988 and 1990.

In February, the main body of prawns is situated in the northern part of the area with "vacant" space in the vicinity of 33.6° South (or 33° 36′ S). The biomass pattern changes largely from February to April due to movement, and substantial biomass increase is attributable to substantial growth which has been determined by tagging and trawl sampling. *The pattern in June directly reflects the effect of fishing. The large peaks in prawn numbers and population fecundity in the vicinity of 33° 30′ South (Middlebank) in April over 1988 and 1990 are removed by intense fishing by the fleet.*

The results indicate that the SPG fleet has capacity to largely deplete major grounds over short fishing scenarios (5-7 days). Intense fishing reduces the potential for adult dispersal and homogenises an otherwise heterogeneous system. Reduction of spread and dispersal potential is a major management problem. Most, importantly, the risk of stock decline would increase if the integrity of effective or most reproductively "viable" spawning sub populations is substantially reduced. Such patterns may not be reflected by logbook and commercial grade data. In fact, owing to the complex closure/harvesting system in Spencer Gulf it would appear that a number of tools are best used in stock assessment including trawl sampling in areas which are not fished. Other tools include catch sampling, logbook data and mark recapture.

Clark (1982) and Hilborn and Walters (1987, 1992) point out that distribution of fish densities largely determine the relationship between catch rates and abundance. Their conclusions are somewhat trivial to fishers, as they are well aware of this fact. Fishing is not a random process because fish and most invertebrate stocks usually aggregate or occur in "patches" at different times, and so does the fleet.

5. STOCK ASSESSMENT TRAWL SURVEYS, PARAMETER ESTIMATION AND DEVELOPMENT OF PROCESS MODELS

Trawl stock assessment surveys are conducted over wide spatial scale in Spencer Gulf. The surveys have mixed research and management objectives, Carrick & Correll (unpublished) and Carrick et. al (1991). Information from the stock assessment surveys are used directly to develop harvesting plans which are refined by adaptive re-sampling (termed spot surveys) of regions likely to be next fished. The objectives are to minimise capture of small prawns, optimise trawl value and determine the level of acceptable spatial effort for stock maintenance. The latter is not trivial, because it requires a detailed analysis of complex spatial data and studies of fishing power (see above). An important aspect of the work is focused on developing a long term time series of spawner, recruit and environmental data. An understanding of the relationship between the numbers of spawners and recruits (SRR), recruits and spawners (RSR) and environmental factors is of paramount importance to management. This research segment is a substantial work beyond the scope of the current FRDC study. Accordingly, an aspect dealing with spawner recruit relationships is **one of the key factors likely to have effect on recruitment is the number of viable spawners.** The FRDC grant has enabled additional fundamental research to be undertaken with focus on recruitment, spawning studies (albeit incomplete), larval distribution and dispersal, postlarval settlement, juvenile distribution, survival and emigration. The work will, in the future, "dove-tail" all components and attempt to further refine sampling and research with a view to making it maximally cost-effective using the superb manpower and vessel sampling power within the Spencer Gulf fishery.

As indicated, it is beyond the scope of the FRDC study to provide detail relating to complex time series of relationships between spawners and recruits (SRR), recruits and spawners (RSR) and environmental change. A paper by Penn et al. (1995) is most relevant as it provides evidence of relationship between spawners and recruits using catch rates from logbook data in Western Australian tiger prawn fisheries. Penn et. al (1995) found that spawning stock (S_t) resulting from recruitment (R_t) was dependent on weekly patterns in fishing effort and was closely approximated by the function $S_t = aR_t\exp(-bE_t)$ where E is the fishing effort. Most importantly, Penn et. al (1995) derived a relationship suggesting a dependence of catch on recruitment and fishing mortality. An excellent review of spawner recruit relationships in crustaceans, and problems associated with assessment and modelling, has been documented by Caputi (1993).

Penn et. al (1995) concluded that decline in tiger prawn production in Shark Bay from early 1980 compared to the high levels of the 1970's was attributable to recruitment overfishing and escalation in effective effort which exceeded equilibrium yield. Recently, Wang and Die (in press) examined spawner recruit relationships and recruit spawner relationships in tiger prawn stocks of the Northern Prawn fishery (NFP). They adapted the basic concepts outlined by Penn et. al (1995) and Caputi (1993). Wang and Die found that there was a relationship between spawners and recruits using a Ricker type model for *P. semisulcatus* (R^2=0.52). Similarly to Penn, they found that for both tiger prawn stocks most of the variability in stock size was attributable to recruitment and fishing mortality.

Wang and Die point out that recent reductions in total fleet fishing days and the number of units in the NFP have not resulted in significant increase in recruitment which occurred in Exmouth Gulf, Western Australia. The authors also point out that both spawning stock size and recruitment of tiger prawns have not varied greatly over the last ten years and that information confirms that recruitment overfishing has been occurring over long term in the NPF.

In summary, Wang and Die concluded that fishing effort on tiger prawns in the NFP is excessive. However, the effect of environmental perturbations or long term change needs to be considered. Moreover, both Penn et. al (1995) and Wang and Die assume logbook data to be reliable, unbiased and without error over the longer term. If the latter is not the case, then the models, estimates, trends and conclusions drawn may be misleading; hence industry must be made aware of the fact that reliable data is required over long term for stock assessment.

It is pointed out that severe reproductive depletion can occur over short fishing periods, irrespective of the amount of "effective effort" (personal observation). The general relationship that F=qf may not be appropriate in many fisheries under intense fishing pressure or where there is high patchiness and large aggregations of prawns. The most reproductively viable spawning units in a stock could be largely reduced before spawning due to aggregation and targeted fishing operations. Therefore, the best controls in a fishery have something to do with: how much exploitation or escapement occurs on spatial scale (c.f. global), when and where fishing takes place. A global constraint on fishing effort may not be an adequate control in management. It appears clear that the models developed for SRR and RSR relate to large global systems and these may not be appropriate in stock assessment in fisheries under high exploitation. Error in modelling the SRR may arise from a serial correlation in the recruitment index. That is, recruitment being affected by a long term environmental factor (eg climate change, nursery habitat decreasing over time etc). A serial correlation in recruitment will result in significant autocorrelation of residuals in SRR.

5.1 Objectives

(a) Statistical modelling, parameter estimation and understanding of spatial dynamics.

The research has the following objectives:

- determine annual levels of recruits and spawners over a decade of time series data;
- determine whether a spawner recruit relationship exists;
- determine effective effort levels which would maintain recruitment and resource sustainability;
- determine the influence of temperature on recruitment;
- evaluate the effects of fishing by fleet manipulation and monitoring;
- determine important fishery parameters (growth, mortalities, dispersion, q);
- determine the relationship between spawners (egg production), post larval settlement to nurseries numbers of juveniles and recruits to the grounds;
- determine strategies to maintain recruitment to the fishery.

(b) Process modelling and development of harvesting strategies.

The objectives of this segment are a major ongoing research program with the objectives being:

- develop spatial harvest models to maximise return and minimise the risk of recruitment overfishing using parameters and information derived from (a);

- compare length based estimates of stock using logbook and commercial size data with survey estimates.

It is pointed out that the objectives stated above are beyond the scope of the FRDC program, but are outlined so that those general objectives defined in the grant application are linked and focused to the main purpose of the work. That purpose is to develop harvesting strategies which result in resource sustainability and long term profitability which requires address to a number of the objectives, including those detailed above.

5.2 Methods

Owing to the scope of the work, the need for longer time series, and the substantial analyses undertaken, only a number of segments are reported. Stratified sampling plans are used in the northern area because within any region there can be large differences in prawn size attributable to location, that is, both abundance and size have systemic spatial pattern. *The differences in size and abundance within a location are of major importance to management.* Sampling in the northern Spencer Gulf is focused on sampling along a major channel within 3 strata over a subset of Blocks (13-19) or sub regions, with one replicate trawl (2 n.miles) taken within each strata which is regarded as independent. Fishing has no effect on recruits to grounds because they are not fished (ie spatially closed to trawling). Both density and abundance estimates based on area swept methods are used in analysis which has direct link to a GIS system, (see Figure 21).

Sampling plans in the southern part of the gulf include 3 major trawl areas (or general spatial units) and include:

(a) Wallaroo
The region is the largest trawl ground in the gulf and has low structure (ie. banks). The region is divided into 10 blocks with one random sample taken from each block to obtain an overall estimate of density and abundance using ANOVA/ANCOVA and spatial statistics to determine patterns in prawn size and egg production.

(b) Gutter
The region is a deep channel with large differences in size across the channel (ie high structure). The region is divided into 9 blocks with 3 strata within each block and one random sample taken from each strata. The region is closed to fishing over extended periods and, over time series, the opening and closing of the region are being addressed by research.

(c) Cowell
The region is a flat plateau with a core of mud situated in the Centre. Three transects or zones are sampled with 7 strata within each zone and two random trawl stations in each strata. However, during February the sampling plan is enhanced to include more sampling sites in the top region to obtain a better estimate of spawners. Similarly, ANOVA/ANCOVA and spatial statistics are used to determine spatial patterns in size, egg production and recruitment.

Sampling plans were modified to increase sampling in the northern section of Spencer Gulf in February to allow greater precision in estimation of spatial differences using GIS techniques, spatial statistics and powerful modelling procedures using AD MODEL BUILDER (Fournier 1994 a, b) and S-PLUS. The systems developed required substantial data base development using DATAFLEX, FOCUS and ARC INFO.

Spencer trawl stations were digitised by D Duncombe-Wall. Spatial data (x, y and z coordinates) were subject to GRID procedures, including kriging, using ARC INFO and SURFER for examination of spatial patterns in prawn numbers, egg production and prawn size. Kriging was examined for reliability and representation of spatial surface fits and for detail in "picturing" spatial pattern. The spatial variation is quantified by the semi-variogram which is estimated by the sample semi-variogram computed from the data.

The sample semi-variogram is calculated from the sample data using:

$$\gamma (h) = \tfrac{1}{2}n \ {}^{n}\textstyle\sum_{i=1} \{Z (xi)-Z(x_i+h)\}^2$$

where n is the number of pairs of sample points separated by distance h. The semi-variogram is modelled by fitting a theoretical function to the sample semi-variogram. The type of kriging used in the project is termed ordinary kriging and it assumes that the variation in z values is free of any structural component (or drift), see Burrough (1986), Ripley (1981).

Semi-variograms for egg production data obtained from a survey in February 1988 were produced using spherical, exponential, Gaussian, linear and circular models. The semi-variogram graphically illustrates how the actual semi-variance vary with the distance between the pairs of original sample points. Figure 21.2 illustrates the actual fit to Gaussian and spherical models. The Gaussian model had a remarkably "good" fit to the actual data therefore and was used in the kriging procedure. The trawl strata, trawl stations on the northern grounds with lightest shading represent higher concentration of eggs. It is apparent that highest egg production concentrations were situated in the northern part of the region and areas of darker shading coincided with areas which were intensively fished.

The kriging was restricted to data obtained from a channel area taken in April 1990 to test the application using "patchy" or localised high concentrations of prawns and eggs. Figure 21.3 illustrates the semi-variogram and the kriged representation of spatial egg distribution. The April 1990 data were not suitable for kriging as shown by the bad fit of gaussian, linear and exponential models. However, the kriging showed a high concentration or "strip" or prawns and eggs along the eastern side of a major bank (shaded red) termed Middle Bank.

There was also a major concentration of eggs in the northern part of the area as indicated by the light shading. Generally, the kriging techniques performs well when variance increases at a low rate but high patchiness and discontinuous data have limitation to the application model. However, even with a bad fit to the model kriging, "pictures" the data and represents main patterns occurring on the grounds.

Simple contouring of prawn size (grade) data were subjected to SURFER to determine the application reliability of differentiating spatial pattern in size of prawns over grounds. Figure 21.4 illustrates the spatial size contours of prawns using same spatial chart generated in ARC INFO for prawn abundance and grades obtained from a survey in April 1988. It is evident that concentrations of small prawns were delineated and that there is a definite gradient in distribution with more smaller prawns (>31/40 and 41/50 and 50+ head-on counts) in the northern section of the area compared to the south. Also, the simple contouring illustrates the gradient of increasing numbers of smaller prawns on the western side of the region. ARC INFO provides a powerful tool for understanding spatial pattern which can be used for stock assessment procedures. The techniques tested were preliminary, and further work using appropriate alogarithms in GENSTAT and S-PLUS are being used for the purpose of developing better techniques for stock assessment over different spatial units.

Error in modelling the SRR may arise from a serial correlation and in time series autocorrelation (acf) of residuals in the recruitment estimate or index.

Caputi points out that: **One of the main concerns in modelling a SRR is the ability to estimate reliably the abundance of spawning stock and recruitment. Standardised surveys by a research vessel usually provide the most accurate indices of abundance of spawning stock and abundance.** Peterman (1990) and Gerrodette (1967) provide excellent accounts of the importance of considering statistical power in fisheries studies for detection of trends, (eg. is the recruitment and spawner biomass declining linearly in time, etc?). However, few studies report on power to detect trend.

Often the spatial sampling (representation) and sample size required to obtain a reliable estimate of spawners or recruits on same moon/tide phase is beyond the capability of a single research vessel. For this reason, there is the need to use larger numbers of vessels using standard sampling gear and consistent methods (ie. sampling plans). By doing this spatial representation, the sampling power is largely increased. The power to detect trend largely increases if there is a major "perturbation" (large decline in recruitment from average), however, in many cases trends may not be detected because of large variance and skew (heteroscadicity) in measures and small change in mean. Better statistical methods avoiding problems associated with normal sampling distributions, skewness and error change in data may be more appropriate. It is surprising that in no study of SRR in Penaeids has reference to power in detecting trend. However, this is likely to be due to the nature of the data and different philosophical approaches in stock assessment. Most studies reported in literature are based on the use of logbook catch and effort data where the unit of effort cannot be accurately quantified or modelled over the long term. The study outlined herein, is a preliminary study of a spatial unit of the stock using survey trawl sampling, and there are a number of shortcomings to be addressed in the future.

The study of spawner recruit relationships in Spencer Gulf has utilised both trawl survey and logbook data and, for simplicity, a small component dealing with SRR in northern Spencer Gulf is dealt with in this report. It is expected that time series of recruitment and spawning stock and weather have auto-correlated error with link to serial correlation's in temperature. A long time series of data and more detailed analysis including Box-Jenkins time series models is being is being undertaken. It must be understood that an eleven year study is a short time series and owing to this there are statistical constraints in ARIMA analysis, (see Box-Jenkins 1970). Cycles in weather may occur over periods of 8-12 years.

Therefore, a time series would need about 16-25 years of data to show effects of weather when recruitment is confounded by fishing of spawners. Another problem is that the spawners sometimes do not vary largely (i. an expected small or undetectable effect). Therefore, spawners may need to be largely changed (or manipulated) over different temporal sequences (high-low), in order to determine relationships and variance patterns.

A problem with manipulation is that risk of stock decline would increase if a linear SRR exists but is not detectable due to noise or error in the data.

Information derived on fishing power was used to estimate effective effort levels (fishing power*nominal effort) and the effective level required for stock maintenance on the assumption that cpue is representative of abundance (see Section 1). However, this is a preliminary analysis, requiring further work on catch, effective effort and recruitment over different spatial units. Moreover, recruitment estimation was planned to be based on four periods of sampling (February, April, June and November). Analysis of these trends are to be reported elsewhere and will incorporate the patterns reflected in the spatial dynamics over time series. It is important to realise that the exploitation levels and cpue are likely to be influenced by the spatial "control" in the fishery rather than effective effort per se, which would mean that cpue could only detect larger differences in stock fluctuations.

(i) Development of a Weather data base.

Data were acquired on disk and tape from the Department of Meteorology, Melbourne and Adelaide in ASCII format with detailed file descriptions. The data on air temperature at Whyalla were summarised and monthly means estimated over each year from 1981-1994. Previous work indicated that there was a significant parallel ($p<0.005$) relationship between air temperature and water temperature at three sites in Spencer Gulf, (viz. Chinamans creek, Whyalla and Port Pirie). Long time series data on tides was provided by the National Tidal Facility, Adelaide (NTF) and used in analyses which will be reported elsewhere. Temperature data from morning (0900 hr) and afternoon (1500 hr) were pooled and mean temperatures for different periods (month, combined months) estimated for the years 1982 to 1994. Data were subjected to time series analyses, see Box and Jenkins (1970), Eatwell et. al (1990) using a number of procedures developed in GENSTAT 5.

(ii) Recruits and spawners

In the study recruitment is defined as the number of female prawns $\leq$ 33 mm CL and male prawns $\leq$ 31 mm CL in February of each year (1982-1994) over northern Spencer Gulf sampling sites. The sampling plan was based on determination of differences in annual recruitment trends (zero, linear, quadratic and cubic) over 17 spatial units (Region) with a split plot sampling plan consisting of Blocks Strata (west-shallow, mid-deep and east-deep) and Treatment Year(10)*Regions (17). Orthogonal polynomial trends were incorporated in the analysis to determine the type and significance of annual trends and effects. Data were subjected to a number of techniques for examination of residuals, including normal scores and plots of residuals on fitted values without and including log and square root transformation.

Owing to the uncertainty of using reliable estimates of egg production, the data on spawners were based on the numbers of larger female prawns (>42 mm CL), following information gained from reproduction studies (see below). The work resulted in substantial data manipulation and output using FOCUS. The relationship between spawners and recruits were based on a 1 year lag (ie. spawners February year 0 on recruits Year 1). Initially, data were subjected to ANOVA to determine annual means and residual patterns of both spawners and recruits and the effects of auto correlated error in time series were examined using procedures written in GENSTAT 5. The distribution in recruitment data were subjected to a number of tests including fits to gamma, normal and log normal distributions. Raw recruit data and square root data were subjected to three tests of normality using methods developed by Aitchison (1986) and Ridout (1993). The implicit assumption in most exponential forms of SRR nonlinear models is of log normality requiring normal approximation of raw data. Subsequently, data were subjected to regression techniques with recruits lagged by one year. Bivariate tests of normality were also undertaken but not discussed in this report.

The assumptions for analysis included :

- That survey data provide a reliable estimate of recruitment and catch rate in the fishery. Previous work has indicated that there is a highly significant ($p<0.05$) relationship between recruitment and catch rate and, in removing an outlier, the linear regression was highly significant ($p<0.001$) explaining 79.2% of variance (see Appendix 4.1). Moreover, the relationships between spatial catch rates in the fishery from surveys and recruitment are being addressed and reported elsewhere. A relationship between survey catch rates , fishery catch rates and recruitment has been established. This was surprising, given the constraints imposed on spatial harvesting schemes, target size and size-dependent mortalities. Therefore, survey trawl assessment appears to be a reliable method of estimation of recruitment to grounds, providing surveys are conducted over consistent periods on dark moon phase, that sampling is representative and temporally intensive (ie. 3-4 periods within a year), and is not affected by fishing.

- That the recruit size selected is representative. This is valid, based on sampling and examination of gaussian size distributions and back calculation of size in sub-nurseries (see above).

- That larger spawners in February produce recruits to the grounds a year later. This appears valid (see above), but the inclusion of smaller prawns and the derivation of a reliable estimation using egg production needs to be addressed.

- Problems relating to time series (serial and autocorrelated error) are removed from analysis. This problem will be dealt with elsewhere as analyses are not trivial, but are incomplete.

- Temperature data are a reliable indicator of some environmental effect on survival or reproduction.

- That density (no. nautical mile) is a reliable indicator of abundance. This has been shown to be valid when sampling is based on consistent and intensive sampling plans.

Data were subjected to :

- time series analysis of autocorrelation in data using Box-Jenkins (1970) methods;
- nonlinear regression (exponential) relating recruits (y) on spawners (x);
- cubic spline interpolation of trends;
- multiple regression using procedures for examining the effects of adding and dropping variates;
- general linear models;
- comparison of regressions fitted through the origin on assumption that zero spawners generate 0 recruits.

It is pointed out that the work is a preliminary analysis, and more powerful statistical and analytical tools are being used to determine relationships. The use of logbook data and factory gradings in derivation of SR and RS relationships over long time series requires care, as most statistical assumptions are violated and results could be misleading and incorrect. It is pointed out that it would not be possible to obtain a meaningful, or unbiased, estimate of effective effort over the long term due to a high level of uncertainty in regard to vessel physical attributes and gear, mesh size, different target sizes, different fishing areas, strong effects attributable to catchability differences, and unreliable and unrepresentative size (grade data) and catch histories (see above).

5.3 Results

(a) Temperature patterns

A smoothing spline fitted to temperature data is illustrated in Figure 24. Variance accounted for was 73.7% of variance indicating a good fit to the model. The results indicate that:

- annual air temperature trends are strongly cyclical which is expected to mirror trends in shallow water nurseries . Background studies shown that the relationship between air temperature and shallow water (<3 metres) have consistent parallel trends;

- there was a large serial decline in temperature from 1982 to 1987 with a subsequent increase in temperature from 88-91 which was followed by a large decline (lowest) in 1993;

- if temperature alone affects recruitment then recruits would be expected to show a cyclical response over time series in absence of spawners or, if spawners are removed in analysis, the effect of temperature would be significant.

(b) Recruitment trends and relationship between spawners and recruits.

Annual recruitment patterns in northern Spencer Gulf were estimated using trawl sampling. The percentage departure from the series mean (2118 recruits.nm) ranged from -28.6 to 36.4% with lowest recruitment (1511 recruits. nm) having smallest variance, variance/mean ratio and catch. Residual patterns for untransformed and square number were satisfactory, however, the effect of log was too strong resulting in skew-to-right. The results indicate that a significant linear/quadratic trend occurred in recruit numbers over Year and that there were significant differences in numbers of recruits over different Regions, with the response changing (ie. Year*Region interaction). The non-central F parameter was estimated and power to detect affects and trend was found to be high (>0.8), Gerrodette (1967).

From histograms of raw and transformed data and fits to distributions, there was indication that recruit distribution was geometric. Square root and un-transformed data were better fits to normal tests than log number. This was also evident from residual patterns. For studies of SRR in Penaeids, usually the time series of annual recruitment has not exceeded 20 and it is unlikely that valid assumptions can be made concerning residual patterns or lognormality.

There was a high correlation between spawners and recruits (0.86). For time series it is noted that:

- The autocorrelation (acf) in numbers using lags up to 5 were small in spawners and recruits.

- There was no indication for a need to correct for autocorrelations in regression using a transfer function model for this preliminary analysis of SR relationships.

Autocorrelations in spawners were low as there was no indication of strong positive correlation at any lag (ie. no periodicity). Similarly, autocorrelation in recruits was small and no strong evidence of periodicity was apparent. However, the time series is short. Box-Cox time series model (TSM) indicated a residual variance (or innovation variance) of 0.5941 and 0.489 for spawners and recruits, respectively.

A simple linear regression of spawners on square root recruits was significant ($P<0.05$) and explained 71% of variance. Multiple regression of spawners on square root recruits and temperature, resulted in regression accounting for 83.4% of variation with a highly significant spawner regression coefficient ($t=5.49$), indicating a strong effect of spawners on recruitment. GENSTAT was used to fit standard nonlinear functions using a modified Newton method of maximising the likelihood using stable forms of parameterisation (see Ross 1990).

A nonlinear exponential model fitted was Recruits =A +B*RSpawners(R>1).** The curvature increased upwards and was strongly influenced by an outlier. The regression was significant ($p<0.05$) and explained 40% of variance suggesting that numbers of recruits are dependent on numbers of larger spawners. On removal of the outlier, linear regression explained 77.9% of variance with a highly significant spawner coefficient ($t=4.75$). The analytical relationship was Recruits = 2494.8-1.84E + 12*0.745**Spawners, (see Figure 25 and Appendix 4.2).

(c) Relationship of recruitment with spawners and temperature.

Initially, the numbers of spawners and recruits were logged with temperature included in a multiple regression. Results indicated that both spawners ($t = 4.01$, $p=.004$) and temperature ($t=2.7$, $p=0.037$) influence recruitment, with multiple regression being significant ($p=0.008$). This explained about 70% of variance in data. The Durbin-Watson statistic used to determine autocorrelation using residuals was 1.85, implying autocorrelation. However, it is pointed out that statistical literature indicates that at least 50 sample points (ie. 50 year points) are required for reliable tests of first order correlation using this method. Study of residual patterns indicated a strong effect of one year.

Multiple regression was undertaken with and without the outlier and the change in residual mean squares and regression coefficients examined for each variate ie. spawners and three periods using mean temperatures. Table 5 provides results of MS estimates, regression coefficients and t-values.

The results indicate that:

- With and without the outlier, the effect of spawners is significant ($p<0.05$) with t values being 2.86 and 4.75 respectively and linear (untransformed) regression explaining 41.9 and 70.6% of variance.
- The addition of temperature 1 (July-December) resulted in a substantial reduction in error MS and decreased further by addition of temperature 2.
- The most significant coefficient in all cases was spawners followed by temperature 1.
- A negative slope of temperature 2 and 3 is apparent and cannot be adequately explained. High temperatures may have negative effects (eg. desiccation) as average air temperatures over summer periods have exceeded 46° C (personal observation).
- With and without the outlier, the regressions using spawners and temperature 1 explained 60.5 and 80.6% of variance, and inclusion of temperature 3 explained about 91.8% of variance in data.
- When spawners are dropped in the analysis, the variance accounted for in regression using temp1 and temp2 was small (7.6%) and the regression slopes were not significant ($t=0.94$, 0.19 for temp1 and temp2, respectively). For regression of temp1 on recruits, the variance accounted for was relatively small (27.3%) and the slope was not significant ($t=2.18$ at the 0.05 probability level).

(d) Discussion

The study is the first attempt to establish a significant spawner recruitment relationship in Penaeids using trawl survey sampling. Therefore, it is expected that the work has merit, as other studies using long time series of fishers log book and commercial size (grade) data are likely to have strong bias and error. Further analysis is required including the relationship of different spatial units of spawner numbers and egg production on recruitment. It appears likely that cyclical trends in weather effect recruitment.

It is obvious that if over fishing coincides with an unfavourable environmental event (or effect) there is high risk that recruitment and stock will decline.

From Figure 25, it appears that from 90 spawners/nautical mile, the resultant recruitment appears approximately constant and, from 85 spawners/nautical mile, the recruitment is largely effected. A reduction of 95 to 80 spawners would result in a 15.8 gain in yield and a loss of 12% in future recruitment. Reduction from 95 to 75 spawners would result in about a 20% gain in yield, but an expected decline of 80% in recruitment.

The 95 spawners/nautical mile represent 28,774 hours (77 days) nominal effort, or about 35,680 hours (95 days) in current effective effort estimates. This result indicates that effort should not exceed about 80 days per annum, in order to maintain recruitment. However, this would depend on the levels of recruits, the spawning stock, spatial structure and exploitation patterns. When the recruitment is large, more effort (exploitation) than 80 days could be applied. Alternatively, when recruitment is low, less than 80 days may be needed to maintain the stock. It is important to realise that management must be adaptive and the estimates provided are a preliminary examination of results using spawner recruit relationships and fishing power to estimate effective effort.

Penn et. al (1995) used a Ricker model in examining the relationship between spawners and recruits in the Shark Bay tiger prawn fishery. They found that the SRR explained about 50% of variance in recruitment which is relatively low compared to that in Spencer Gulf (cf 89.8%). The exponential analytical model used in Spencer Gulf has been enhanced and detailed assessment of time series relationships are being undertaken. It is pointed out that even 15 years is too short a period for time series analysis of spawner recruit relationships. Further tests could be undertaken with industry in changing spatial spawner levels, however, this poses a risk of stock decline.

6. REPRODUCTIVE DYNAMICS

6.1 Background

Courtney and Dredge (1988), using histological sectioning, found that the minimum size of post-vitellogenic females (mature adults) of *P. latisculcatus* in Queensland was 34 mm CL and did not include sizes smaller than this in estimates of population fecundity. Courtney and Dredge found that the smallest female inseminated was 27 mm CL. Insemination increased exponentially as size increased, reaching a level of 95% at around 42-44 mm CL. They also found that *P. latisculcatus* spawned throughout the year with a peak in winter which contrasts with *P. latisulcatus* in South Australia. Penn (1980) found that females less than 28 mm CL were rarely mated in Shark Bay (22° south) and Cockburn sound (32° S). However, the allometry differs between Western Australia and South Australia (unpublished). Penn found that female *P. latisculcatus* are physically mature at 25 mm CL and the smallest ripe female was 29 mm CL which contrasts with the study undertaken by Courtney and Dredge (1988). Literature indicates that in Penaeids the proportion of ripe females at any one time infrequently exceeds 30%. Penn (1980) found that *P. latisculcatus* spawns throughout the year in northern latitudes (22°-26°S) in Western Australia whereas in southern Western Australia, Cockburn Sound (32° S) spawning was restricted and occurred from December to March.

6.2 Objectives

(a) *The study was set up to :*

(a) Determine the spatial trends in maturity, based on macroscopic staging and histological sectioning.

(b) Determine whether there were significant differences in maturity and spawning sequences between size groups and between sub-populations (spatially separated but linked by movement).

(c) Determine whether lunar phase and temperature effect spawning and whether there are significant differences in trends in spawning between years.

(d) Determine the relationship between female prawn size and the percentage inseminated and fecundity at different regions.

(e) Derive analytical functions for spawning patterns and egg production required for an advection/diffusion model.

(f) Determine the relationship between moult cycle, insemination and spawning and to test whether partial synchrony in moulting occurs.

(b) Field and Laboratory Methods

Macroscopic staging was used to quantify the maturity status of female prawns using a modification adapted from Tuma (1967), Cummings (1961), Lightner (1983), King (1948), King (1978), Yano (1988), Crocos and Kerr (1983), among others. Six geographical regions were sampled by trawl gear over two-week to monthly intervals from October to April in 1991/92, 1992/93 and 1993/94.

At each site a sample of approximately 400 prawns were collected and sexed, with females staged and measured immediately on capture prior to post mortem colour changes. Gonad colour and form are lost if samples are not measured or snap frozen immediately (personal observation). For *P. latisulcatus* it is virtually impossible to reliably stage prawns if in brine for longer than 2-3 hours, or if left for 1 hour on deck. Contrary to Penn's generalisations it is well known from field observations that *P. latisulcatus* displays a gonad colour range from transparent, translucent to white, to white -yellow to yellow, to deep yellow to orange. The olive/greenish colour typical of tiger prawns is infrequent and may be associated with gonad absorption.

The following criterion were used in staging:

Stage 0. Ovary not evident. Intestine and muscle visible when head bent.

Stage 1. Ovary translucent to milk-white. Intestine not visible.

Stage 2. Ovary is white-pale yellow, lemon -white. Ovary not visible through carapace.

Stage 3. Ovary is lemon-yellow to yellow and clearly visible in carapace and tail. Can see post orbital lobes. Chromatophores beginning to develop.

Stage 4. Ovary is yellow orange. Finger like lobes clearly visible in carapace and extend largely through carapace. Post orbital lobe prominent and chromatophores. Sometimes ovary greenish/yellow to olive. Ovary clearly visible in head and extending through tail segments.

The spent stage is not possible to identify by macroscopic staging but field observations from spawning in circulating tanks indicate that ovary is "clear" with "black streaking" along the position of gonad in tail.

The problems with macroscopic staging are:

- it is not possible to separate recently spent (ie post 4) stages from stage 0;
- difficult at times to separate late stage 2 from 3 and stage 3 from early 4 or from stage 1 to 2;
- partial spawning occurs and colour changes of individuals re-absorbing ovary in carapace appear yellow/olive but re-absorption characteristics have not been supported by sufficient sectioning for validation.

Scatter plots of maturity on time (approximately 2 week intervals) from October 1992 to June 1993 for each station, were plotted to examine evidence for double peaks in maturity. On the assumption that there was evidence for two recruitments to the fishery, (February and June), one could expect two spawnings over the breeding season (November to March). The sampling plan consisted of three geographical regions, with two situated north of 33° 15° S and one south of 33° 30° S. Logistic and cost restrictions prevented more intensive sampling over wider geographical scale, (eg. south of 34° S). Two stations within each region were used as replicates to determine differences in maturity of time. Region 1 consisted of sampling in the vicinity of Station 42 and Station 27, Region 2 sampling took place in the vicinity of Stations 22 and 21, while Region 3 consisted of a random sample taken in the vicinity of 2 and Wallaroo Stations 8 and 2 (see Figure 26). The sampling plan aimed to incorporate latitude, depth and water temperature as covariates. An attempt to increase geographical sampling (wider range of Regions) and replication was undertaken but was abandoned due to logistics.

Mean maturity for each Region was based on 13*2 sampling units from 23/10/92 (month 0) to 18/4/93 (month 5.9) with data subjected to nonlinear regression to test for gaussian (1 mode) and double gaussian (2 peaks) in maturity over time. The objective was to determine whether a double gaussian had a better fit to the data than a single gaussian model. A significantly better fit by a dgaussian model would provide evidence that two maturity cycles occur and therefore two spawnings are likely to occur within the breeding season. Corroborative evidence of two peaks in early larval numbers would support the hypothesis that two spawnings occur within a single breeding season. It is noted that past field observations (fishing operations and surveys) indicate that reproductive development or spawning does not occur from May to August/September. That is, field observations suggest that spawning was restricted in time and took place from late spring to early autumn.

Tests of gaussian versus dgaussian trends in maturity included the following tests:

- An F test comparing the residuals using F(2,6)=(RSSg-RSSdg/Dfdg)/MSdg.
- A non parametric test of the observed versus fitted values of each model for each Region using the Kolomov-Smirnov test (see Siegel 1956).
- Maximum likelihood tests using the deviance.

A random sample of 10 individuals were taken from 8 size groups (viz. 20-24 to 60+mm CL) and preserved in buffered 8% formalin in sea water. For each individual, the first two abdominal segments and carapace (including the thelycum) were preserved with an incision through tissue to allow penetration of fixative. A further sample of 50 individuals was taken at selected sites and each individual measured, staged, and number tagged to allow identification on sectioning so that macroscopic stage could be compared by TS section. From tagged individuals, 3 pleopods and the telson /uropods were removed and fixed in Davidson's fluid for sectioning to determine moult stage relationships. Field logs of degree of softness was noted for comparison to TS sections. Owing to the need for file manipulations a data base was set up using DATAFLEX for entry and FOCUS for programmable reports and data manipulation.

The Flinders Medical Centre (Anatomy and Histology Unit) carried out preliminary work on gonad histology from samples collected. Both freezing and paraffin embedding were used and 5 histological stains tested, including Masson's, Mallory's trichrome and Hematoxylin/eosin. TS sections of the postorbital lobe were used and it was planned to test for homology in vitellogenesis between along the gonad.

An Image analysis system (Leading Edge, South Australia) was linked to a Leica compound microscope and software developed to allow rapid measurement and storage of attributes and images. Owing to the amount of difficulty and the time required for the larval work the program relating to histological sectioning is yet to be completed.

6.3 Results

(a) *Histological Sectioning*

Harris' Hematoxylin/eosin and paraffin embedding showed best results for sections cut at 5-8 microns, see Figure 27. Preliminary work indicated that the following attributes could be used in quantifying maturation and spawning:

- oocyte size;
- ratio of nucleus size to cell diameter;
- position of nucleus;
- position of chromosomes;
- density of chromatin in nucleus;
- presence and position of follicle cells within the oocyte.

The work, although not complete, showed that specimen preservation and fixing techniques were satisfactory and image analysis proved a valuable tool for examination of high quality sections undertaken by a professional histologist. It is planned to continue the work with Flinders Medical Centre and Adelaide University in the future.

(b) *Seasonal patterns in maturity and spawning based on macroscopic field staging*

The spatial trends in maturity are based on 28,000 individuals measured over 14-16 day periods from October 1992 to June 93 (13 sampling periods) are illustrated in Figure 28. Greater detail will be provided in future reports and publications.

The following points are noted:

- There is a general pattern for two peaks in maturity or ripeness (ie. stage 3+4) with the first peak in mid December and another in early January.
- Spatial differences in maturity are apparent with indication that the larger prawns at station 22 (north) and station 8 (south, Wallaroo) spawn earlier (ie. from late November to early December).
- A well defined bimodal peak in maturity occurs in larger prawn subpopulations.
- At stations 21 and X2 a well defined decline in ripeness occurs from mid December to early January suggesting a well defined and possibly synchronous spawning over this period.

Data from all sites were subjected to a nonlinear program written in GENSTAT 5 to determine whether ripeness has a double gaussian trend which may be attributable to multiple (2) spawning of larger prawns or spatial (geographical) differences in maturation. That is, two bell shaped peaks in maturity with an unknown lag (expected to be 7-14 days from peak ripeness to spawning). Figure 29 illustrates the trend in maturity (stages 3+4) pooling all sampled stations over each sampling period (approximately 14 day intervals). The dgaussian regression of percent maturity on period, explained 87.4%of the variance. Information indicated bimodal maturity and therefore two peaks in spawning, (see Figure 29.2).

The Kolomov-Smirnov test proved unsuitable and a general comparison of statistical methods will be presented elsewhere. The F test method indicated that the double gaussian was a better model than the gaussian for all Regions, with each Region having p-values <0.05. Therefore, the analysis demonstrates strong evidence for two peaks in maturity. Table 6 shows the means and standard errors for each model, with month being the time (1 unit = 30 days) from 23/10/92 (month 0). The dgaussian model indicated that the first peak in maturity occurred at month 1.48, 1.5 and 1.6 for Regions 1, 2 and 3, respectively. The predicted dates for the means for the first peaks fall between 6-7 December. If spawning occurs 10 days after peak maturity, one would expect a peak in spawning at approximately 17 December for the northern regions. There was indication that maturity occurred about 4 days later in the southern Region which may be attributable to colder water in that region.

The second peak in maturity occurs at 2.9 month (88 days), 3.4 month (101 days) and 3.5 month (104 days) for Regions 1,2 and 3 respectively. For the second spawning, there is strong evidence of larger temporal differences in maturity between north and south. That is, peaks are expected to occur on the 3, 16 and 19 February for each Region. Comparing Region 1 and 3, there is a 16 day difference in the second mean maturity peak, but only a day difference between Region 1 and 2. Assuming a period of 10 days between peak maturity and spawning, one could expect a peak in spawning on 13 February for Region 1, 26 February for Region 2 whilst at Region 3, the second spawning peak would be expected to occur on 28 February.

The single gaussian peaks in maturity occur at 64, 73 and 71 days from 23 October for Region 1, 2 and 3 respectively. These periods represent January 10, 19 and 17, and peak spawning is likely to occur on the 20 January, 29 January and 27 January for Region 1, 2 and 3 respectively.

No estimations of population fecundity were done because this would be futile without empirical data on insemination frequency over different size. The question of reproductive viability is planned to be addressed by field and laboratory studies (see below).

(c) Size at Maturity

The percentage ripe female prawns from 15-65 mm CL was estimated by pooling all data and truncating at sizes where there were less than 20 individuals thereby restricting data to 25-56 mm CL. Data were fitted to a double Fourier regression and the variance accounted for was 88.6% indicating a good fit, see Figure 30.

Other types of nonlinear fits were not satisfactory.

The following points are of significance:

- There appear to be two cycles in maturity over the size range. A smaller peak at 33-34 mm CL where 20% of the population mature to a ripe stage and a large peak at 48 mm CL where 30% of the population are ripe. The size at maturity appears different to the logistic type appearing in literature and this may be attributable to differences associated with geographical location and a bias attributable to size (age). The effect of size will be examine in the future, using data analysed above and samples preserved for TS sectioning. There may be sub-population differences in breeding.

- Reproductive maturity is low at smaller sizes ranging from zero at 25 mm CL to 8.4% at 27 mm CL.

- The patterns were established by large scale sampling using a subjective method of macroscopic staging and maturity status was not adequately validated by sectioning.

- Egg production patterns and reproductive viability remains unclear and needs to be addressed by additional work.

- Patterns established appear different to other documented cases in Australia for *P. latisculcatus* and contrast with tropical Penaeids which usually have continuous spawning, with peaks in autumn and spring.

6.4 Discussion

P. latisculcatus appears to have a different life history tactic across latitude. In Spencer Gulf, *P. latisculcatus* has a restricted period of spawning with large reproductive effort affecting the growth pattern. Growth is slow over the spawning period even though temperatures are increasing. The species has a relatively long lifespan. Adult mortality varies with size (age) and appears lower than most documented in the literature. Most importantly, high maturity is reached at relatively large size (age) and therefore, main recruits of the year (February) are unlikely to contribute to the viable spawning population in the November to February spawning period (see below). There may be sub-population differences in breeding pattern, however, samples recently collected for the South Australian Museum (B James) and subjected to electrophoresis did not provide evidence for genetic structuring within the population.

The results have major significance to management. The general methodology and concepts for determination of spawner recruit relationships requires critical appraisal. The peak in maturity at larger size is likely to be due to bigger prawns spawning twice (multiple spawning) over the breeding season with the first peak in late November-early December and a second in late January to early February. Alternatively, there may be spatial differences in spawning sequences. It would appear that the peak spawning in December produces most larvae and postlarval recruits to nurseries, however, the timing of maturity (and spawning) and population fecundity can vary annually which is likely to have effect on settlement pattern to nurseries, (see below). The first spawning is expected to produce the June recruits to the fishery while the second spawning generates the over-wintered recruits to nurseries. The over-wintered recruits emigrate from nurseries from December. The February recruitment to grounds is larger in the northern area of Spencer Gulf, while the June recruitment is larger than the February recruitment in the southern area. Such differences in recruitment patterns to grounds are likely to be the result of a number of factors, including temporal differences in spawning and settlement.

For the northern area of Spencer Gulf, the February recruitment strength is expected to have large influence on catches in the northern region from April to May, and on smaller sized prawn catches in the Wallaroo area from March to April, (unpublished).

Indeed, there appears to be a "mis-match" in patterns which is best explained by large differences in survival in nurseries between those postlarvae which settle in December to February (direct recruits) and postlarvae which settle from mid to late March and overwinter with relatively low mortality during the winter to spring period.

Another mis-match, relates to loss or waste of larvae from large spawning and this may be due to less favourable advection which has similarity to *P. merguiensis* in the Gulf of Carpentaria, as documented by Rothlisberg et. al (1982). Crocos (1987) found that the minimum size at which *P. esculentus* mature was 25 mm CL and the proportion of mature females rapidly increased from 6% (27 mm CL) to 70% (36 mm CL). Crocos found that 50% of females were mature at 32 mm CL and this was regarded as the size at maturity. These results are in contrast to *P. latisculcatus* in South Australia. Also, the general form of the maturity size relationship in *P. esculentus* is Gompertz (beta>0) which differs from that of *P. latisculcatus* in Spencer Gulf. Arnstein and Beard (1975) reported a ripe stage of 12-14 days before spawning in *P. setiferus,* but the lag remains to be determined in *P. latisculcatus.* However, the large decline or change in maturity status from 60% to 26% at site 21 occurred over a 14 day interval.

One could assume for mature prawns (Stage 2 and 3) that there would be a lag of some 10 days before spawning in *P. latisculcatus* at mean temperatures ranging from 19-22° C. Assuming a period of 10 days from peak ripeness in a double gaussian model would result in the first spawning peak occurring in mid December and the second between mid and late January, these results appear consistent with larval studies (see below).

The work demonstrates strong evidence for two peaks in maturity, on the basis that dgaussian model fits the data better than a gaussian model. The timing of maturation and spawning and relative egg production are expected to have large influence on settlement and recruitment patterns to grounds. It is not speculative to expect that a delay in spawning due to environment (eg. colder water temperature) will result in late settlement to nurseries and low levels of recruitment to grounds in June. The amount of reproductive depletion from October to February has been of concern. Management introduced constraints on fishing over this period, while being adaptive and responding to changes (see below).

It is evident that realistic comparisons of population fecundity and effective spawners cannot be made without a weighting factor for reproductive "viability and abundance". Penn (1980) reported that in Cockburn Sound, a region of similar temperature to Spencer Gulf the spawning and population fecundity of *P. latisculcatus* reached a peak in early February just prior to maximum water temperature. This does not appear to be the case in Spencer Gulf where spawning has two peaks, as verified by larval sampling (see below). Penn noted that only one recruitment peak (autumn) occurs in the Cockburn sound grounds in contrast with Spencer Gulf which has two well defined recruitment peaks to grounds (i.e. February and May/June). For Shark Bay, a warmer temperature regime, Penn found that *P. latisculcatus* generally spawn throughout the year with two peaks in population fecundity, the largest occurring in May (autumn spawners) and another in August/September (spring spawners).

The life history tactic in Penaeids can differ with latitude. The "sustainability" of heavily exploited Penaeid fisheries has a close link to spatial pattern, reproductive viability and dispersal. Further work in Spencer Gulf is required to ascertain patterns in spawning and for estimation of insemination from samples already collected which could not be undertaken in the program due to problems and manpower.

There was a priority need to obtain larval information over 2 spawning cycles (2 years) in order to obtain parameters required for modelling and in order to validate assumptions of other research segments. The spawning results are based on a subjective field method (macroscopic staging). Further work by histological sectioning should enable both maturity and spawning sequences to be clearly quantified and comparisons made between years and, most importantly, over different spatial units. **The insemination frequency of different size prawns must be determined to allow better harvesting practices to be developed and for detailing most "viable" spawning units in the population.**

7. LARVAL PRAWN DISTRIBUTION AND ABUNDANCE

7.1 Background

The importance of life history tactics and larval dispersal to maintenance of populations has been reviewed by Strathman (1974), Underwood (1974, 1979), Scheltema (1982, 1986), Carrick (1980), among others. The most impressive work on the significance of dispersal is that documented by Reddingus and den Boer (1970) and Roff (1974), based on the concept of "spreading of risk". A fundamental understanding of basic larval population biology was needed in Spencer Gulf for knowledge of processes effecting settlement, for validation of assumptions relating to spawning, and for parameter estimates required for an advection -diffusion dispersal model. The use of larval sampling as a tool for stock assessment (effective egg production) has merit, however, the time (and cost) required to obtain results is prohibitive.

A preliminary study of larval distribution indicated that there were significantly larger numbers of larvae in the north than in the south and that large annual differences occur, (FRDC reports). Another problem relating to the larval sampling was the high degree of heteroscadiscity in data and error change over time.

Carrick (unpublished) advocated that planktonic larval dispersal and subsequent supply to nurseries is expected to be influenced by many factors including:

- circulation patterns induced by currents, tides, wind stress, density structure, storm surges and pressure systems;
- temporal and spatial egg production and adult dispersal;
- larval vertical position and environmental cues or clues;
- duration of planktonic phase or length of larval life;
- differential survival of larval stages.

It was hypothesised that for an oceanic Penaeid fishery like Venus Bay, South Australia, a large scale change to near shelf oceanographic conditions was a likely mechanism influencing spawner aggregations and successful advection and/or supply to nurseries. A mismatch in conditions or change in phase at a critical period may have large effect on postlarval larval supply to nurseries and could result in population "crash". A favourable change in oceanographic conditions at low spawner levels can result in substantial increase in recruitment, providing spawner spatial distribution is not disturbed by fishing. Factors which change dispersal are of importance if there are biological or adaptive cues for aggregation or spawning in key locations and this has been referred to as the "light-house" effect. Spawning and successful dispersal cannot be a random processes in the Venus Bay fishery. Cues are likely to match environmental conditions.

Rothlisberg et. al (1983) reached a similar conclusion indicating random diffusion of larvae could not explain the seasonal changes in larval transport that may be responsible for loss or waste of *P. merguiensis* larvae from a major spawning. Talbot (1977) suggested that diffusion was not a important factor effecting the dispersal of plaice eggs in the North sea and Okubo (1980) provided simple models suggesting that diffusion cannot be a strong forcing factor in dispersal and population maintenance. Wind stress in the night may be a mechanism which can return or redirect larvae to nurseries, especially if mysis or postlarvae migrate to surface waters in night. A change in current direction over critical larval periods would therefore have substantial effect on populations, if supply to nurseries is limited by and linked to finely tuned biological and physical processes.

The study of larval dispersal is a complex phenomena requiring the combined skills of physical oceanographers, biologists, statistical modellers and applied mathematicians. There is a definite need to obtain empirical real time data on surface winds, to measure currents and to test models directly in the field.

Dispersion models simply cannot be tested by simulation or "calibration " without the field measurements of currents and wind and by statistical tests of expected responses using empirical real time field data (eg. larval distribution, settlement).

Most importantly, many researchers have attempted to correlate environmental time series events with some measurable biological parameter (eg. recruitment) but may never understand the underlying factors structuring or forcing recruitment simply because the main events, dispersal of larvae and pattern in settlement are not adequately understood. On worse case scenarios, a correlation of recruit numbers with some physical or environmental measure (s) may occur and often biologists imply a cause/effect situation which could affect fishery management strategies. Alternatively, biologists could neglect the association of environment and attribute variation to over fishing based on general "ad-hoc" models, which could result in a substantial waste of a resource. It needs to be understood that small changes in larval life history parameters (eg. survival, length of larval life etc) can have large effect on model output because of multiplicative effects in nonlinear systems (eg. Keesing & Halford, 1994). Change to normal patterns of larval advection may also result in a large effect on settlement pattern.

Previous studies of Penaeid larval distribution in Australia are limited to the excellent work undertaken by Dakin (1938, 1946), Dakin and Colefax (1940), Racek (1959) and the CSIRO studies in the Gulf of Carpentaria and Morton Bay as reported by Rothlisberg (1982, 1988), Rothlisberg et. al (1983 a), Rothlisberg et. al (1983 b), Rothlisberg et. al (1985), Rothlisberg and Jackson (1986), and Jackson et. al (1989).

The work described below is the first dedicated study of the larval population biology of *P. latisculcatus.* Major problems faced by most workers in this field relate to: the difficulty in identifying or separating species and larval stages, usually low numbers (count data) and/or highly skewed distributions, high costs associated with boat hire, sampling gear, expertise and manpower required in sorting/identification and capital costs for field and laboratory equipment.

Temple and Fischer (1965) investigated the larvae at three depths off Galveston, Texas and in pooling species found that early larval stages (zoea and mysis) were more common in deeper depth strata (18 and 34 metre) while postlarval stages were more frequent in the upper (2 metre) strata. Changes in vertical distribution of each larval stage showed evidence of vertical migration with all stages moving into the surface depths at night. It is important to note that the postlarval and mysis stages moved up earlier and stayed longer at the surface than zoea. The workers also found that vertical mixing effected vertical distribution and there were apparent seasonal differences attributable to the degree of mixing.

Jones et. al (1970) used open plankton nets in a study of the pink shrimp *P. duorarum* off Florida and found that for most samplings there were more larval stages on surface layers at night, while in the day more were captured near the bottom. Postlarvae were more common in mid to upper layers while earlier stages (zoea) were more common near bottom layers with myses common throughout the water column during night, but infrequent in surface strata during the day. The authors suggested that the larval stages respond differently in diurnal vertical movement and that postlarvae have higher mortality than earlier stages.

Rothlisberg (1982) investigated prawn larvae vertical distribution and response to light using a large pump to sample different depth strata (4) in the Gulf of Carpentaria. There was evidence of a day/night vertical migration but analysis was constrained by low numbers and frequent zero counts. Rothlisberg found that patterns were noticeable when light penetration was low and a ontogenetic increase in vertical migration ability was evident. Whereas zoea had restricted movement in bottom layers, mysis moved up middle layers and postlarvae moved from bottom to surface at night. Diurnal vertical movement appears consistent in Penaeids and it is likely that different patterns documented in the literature reflect differences attributable to degree of water mixing, light penetration and possibly sampling gear and methods. The excellent work of Rothlisberg (1982) and Rothlisberg et. al (1983 a) on vertical migration and cues clearly indicates a case for a homogenous pattern in Penaeids.

Larval dispersal and advective potential is influenced by spatial sequences in egg production, current movements and vertical migration behaviour. Studies by Rothlisberg (1982) and Rothlisberg et. al (1983a) demonstrated that in combination current speed, direction and larval vertical behaviour had large effect on larval dispersal patterns. It was pointed out that water transparency would effect dispersal because in turbid water larvae were higher in surface layers and accordingly follow a dispersal trajectory following surface currents, whereas in clearer water the trajectory would follow bottom currents. Rothlisberg et. al (1985) estimated by modelling that over 14 days larva could be advected 70-100 km.

A model was developed to clarify seasonal and temporal patterns in postlarval settlement using input on larval behaviour, hypothetical spawning and egg production at different areas using a 2-dimensional current model in the Gulf of Carpentaria.

The modelling showed that:

- vertical behaviour enhanced horizontal advection;
- seasonal variation in direction of dispersal was apparent;
- different spatial units under different diurnal current regimes and same vertical migration pattern displayed large seasonal differences in dispersal direction.

It was concluded that the relatively small egg production of banana prawns, *P. merguiensis* from the smaller spring spawning resulted in higher postlarval settlement because of more favourable (onshore) advective forces. Whereas in the larger autumn spawning larvae are transported offshore and away from nurseries, resulting in substantially lower numbers of settlers than from the low spring egg production. Rothlisberg et. al (1985) points out that advection alone, in the case of *P. merguiensis* in the south eastern Gulf of Carpentaria, would account for the apparent mismatch between the minor peak of spawning and the major peak of postlarval recruitment.

Johnson (1985) reported that the timing and the magnitude of change in wind stress in inshore and offshore regions of Chesapeake Bay, Virginia, is a major cause of recruitment variation in the blue crab, *Callinectes sapidus*. The larval biology of the blue crab has similarity to Penaeids. That is, larval life is relatively short (36-50 days to reach first juvenile stage) and a vertical migration occurs. Workers found that vertical migration in the blue crab occurs in phase with tides in a mixed system and, in stratified waters, vertical migration is less evident (Epifanio 1988). Johnson (1985) applied numerical simulations of blue crab larval dispersal and recruitment near the mouth of Chesapeake Bay, Virginia and found that wind direction and strength has large effect on recruitment or settlement. The study has relevance to the West coast prawn fishery as main spawning occurs offshore but favourable settlement would be limited by the narrow entrance at Venus Bay (<1 nautical mile).

Rothlisberg and Jackson (1987) found large differences in salinity and temperature regimes in the distribution of different larval Penaeids in the Gulf of Carpentaria. They found that the mean temperature and salinity for *P. latisulcatus* was 27.3° C and 34.9 ppt. Penn (1980) pointed out that spawning in *P. latisulcatus* takes place in oceanic salinities in Shark Bay , Western Australia. However, in Spencer Gulf spawning is widespread over the Gulf and it is certainly not limited to "oceanic" salinity regimes as ripe individuals have been frequently observed in hypersaline environments, (eg >42 ppt, personal observation).

The information contained in this study besides being one of the few studies of larval Penaeids undertaken in Australia is the first major study of *P. latisculcatus* . Moreover, it is one of few larval studies which have addressed temporal change in distribution and models trends. The study is one of few which has obtained a reliable estimates of larval survival. However, the analyses presented are a preliminary assessment and further analysis completed but not reported here will enhance the project.

7.2 Objectives

The objectives of the study were:

(a) Determine seasonal and spatial trends in abundance. In particular work was focused on:
- test of differences in latitude, aspect (sides and middle of Gulf) and depth;
- test of whether a seasonal change or different response in spatial distribution occurs (ie. Time*Latitude interaction).

(b) Determine whether bimodal peaks in larvae occur over the breeding season.

(c) Test and validate patterns in maturity and spawning.

(d) Determine relationships between larval numbers and salinity and temperature.

(e) Determine whether differences in annual patterns occur and whether larval sampling can be used as a tool for assessment of "viable" reproductive levels.

(f) Determine whether high larval numbers result in large settlement.

(g) Determine length of larval life.

(h) Determine which spawning contributes most to egg production.

(i) Estimate larval survival and verify maturity and spawning patterns.

(j) Determine diurnal movement pattern.

7.3 Field Methods and Sampling Plans

(a) Larval distribution -temporal and spatial pattern

There was no relevant background information relating to fine mesh plankton sampling in SPG and limited funds were available to purchase plankton equipment. The sampling gear and techniques needed to be developed and tested prior to the design of a sampling plan. It was initially thought that Spencer Gulf would be of a "blue-water" type (see Smith and Richardson (1977) due to low nutrient status, thereby reducing problems associated with clogging of mesh at small mesh size and the net design. A system was required to be developed that was simple and least expensive. The sampling method needed to produce reliable results and avoid problems associated with low and zero counts. That is, large volume sampling was expected and the constraint of clogging required consideration for developing and improving sampling gear.

The SARDI research vessel Ngerin was used for all plankton sampling. The vessel was also used as a mother ship for juvenile sampling in conjunction with a collaborative shore based industry funded operation using trailorable craft. Initially, two sizes of bongo nets (40, 60 cm diameter) and three mesh sizes were tested viz. 120, 250 and 500 microns. The plankton nets used in tests had a mouth to length ratio ranging from 5-8 and were manufactured from Nytal (66 GG) high quality mesh by Swiss Screens (Sydney) using specifications provided.

Five sites were sampled during November 91 to February 1992 with samples preserved in 5% formal sea water and the same volume of preservative used (500 ml). Inspection of nets and samples was undertaken to determine relative performance based on volume by direct visual observation. A few samples from three trials were examined using stereo microscope to determine presence of Penaeid larvae.

The trials undertaken in 1991 and early 1992 indicated that :

- substantial clogging of the 120 micron mesh occurred with low and high mouth/net length ratios;
- the amount of plankton from December-February in both small sizes was substantial;
- minimal net clogging occurred in all high length to mouth ratio nets especially using the 60 cm bongo net, whereas net clogging occurred using the smaller bongo net, (ie. 40 cm diameter) especially the lower length to mouth ratio net requiring substantial washing;
- the sampling method appeared satisfactory based on the presence of large numbers of Penaeid larvae.

It was realised that an enormous sorting problem would occur by using the 120 micron net, as two Penaeids occurred with what appeared to be exceedingly high larval numbers (especially nauplii). Tests in March 1992 indicated greater than 2000 Penaeid larvae in small sub samples. The 250 micron mesh clogged less and contained less small plankters and algae.

It was apparent that the gulf waters were more diverse and productive in terms of biomasss/shot than expected The trials indicated that the high ratio net with 60 cm diameter bongo frames and 250 and 500 micron mesh would provide more reliable results and reduce sorting/subsampling problems. Furthermore, it was expected that the 500 micron mesh would provide a more reliable estimate of postlarval numbers if flow was restricted (clogging) with smaller mesh size. The winch gear and method worked satisfactorily but required high skill in winch operation. Length of cable required to sample bottom layers was estimated using soundings and previous trial and error with cable graduated in 5 metre intervals. Unfortunately, the operations resulted in loss of two sets of bongo nets and damage to four others, because it was difficult to estimate required cable length in conditions of strong tide and wind. Attempts to acquire electronic monitoring of net position in the water column were not successful.

The bongo net was fitted with a closing depth gauge which recorded maximum depth and it was reset after each haul. Sampling occurred across depth. A 30kg weight was suspended from the base of the frame to maintain net position following Smith & Richardson (1977). Oblique hauls from surface to bottom were undertaken using open nets with a General Oceanics high speed Flowmeter (model 2030R) suspended across the mouth of each net. Flowmeter calibrations of counts to distance and net mouth area were used to estimate volume filtered using a method described by Smith & Richardson (1977) and larval abundance was standardised to 100 m^3. Following trials and gear modifications the sampling plan was set up and conducted every 22-26 days from November 92 to April 93 and from October 93 to March 1994 Sampling was based on a fixed plan where 5 latitudinally separated Transects were sampled over each Period. Within each Transect, five stations were sampled across (east to west) the Gulf with two random hauls taken from a fixed 1*1.5 nautical mile grid aided by GPS plotting facility aboard the Ngerin, see Figure 31.

Transect 1 (33° 4′ South) was situated at the top of the Gulf while Transect 4 situated further south (34° 30′ South). Depth on each transect side were similar. Within all Transects, the middle station was deepest and was similar between Transect 1 to 3 (approximately 20-22 metres). The middle station in Transect 4 was 8-10 metres deeper than the other Transects. The sampling plan was discussed with a statistician (R. Correll) and a larval ecologist (C. Jackson) prior to the set-up of the main study and both agreed that fixed plan was best in consideration of objectives.

Sampling plans were based on a 3 way ANOVA to test for polynomial trends over time (Month). During each haul two temperature and salinity measurements of surface water were recorded using a HST conductivity meter (LF 196) with frequent salinity samples taken for calibration (and check on accuracy) using a standard Hamond salinometer at SARDI. All sampling was undertaken after sunset and before sunrise and occurred over similar (dark) moon periods. Unfortunately, bad weather and loss of sampling gear resulted in missing data at critical periods which posed problems in analysis (see below). A removable cylindrical (25 cm * 15 cm diameter) soft cod-end was used on each bongo net (250, 500 micron) and a number of devices constructed to allow expedient removal from codends and sample handling at sea.

After every haul each net was washed with a high pressure hose for approximately 10-15 minutes. The duration of hauling was dependent on depth, weather and tidal conditions with most hauls being 7-10 minutes (surface/bottom).

Data from early post larval stages (zoea 1 and 2) were pooled and used to determine differences in spatial and temporal patterns in larval distribution. The distribution of early larvae was expected to "mirror" maturity peaks. Polynomial trends in early zoea numbers were tested by ANOVA and nonlinear regression was used to determine which type of model had best fit to data and included double fourier, double gaussian and gaussian forms. Data were subjected to programs written in GENSTAT 5 and were log transformed owing to the skew in untransformed distributions. Transects 1 (north) and 4 (south) were used to compare wide scale geographical distribution and it was expected that trends would enable tests of two peaks in larval distribution and therefore two spawnings. The maximum length of zoea 1 and 2 stages was expected to be around 5-6 days, see Hudinaga (1942). Therefore, the analysis was independent, with no double counting.

Determination of seasonal abundance over Transects and Aspect and effects of salinity, temperature and depth were undertaken using ANCOVA and general linear models (GLM). Determination of survival was based on the work of Munro et. al (1968) which was simple differencing using abundance (or rate) and estimates of duration of larval life obtained from Hudinaga (1942) on a related species (*P. japonicus*) cultured at similar temperatures to Spencer Gulf waters.

Munro et al (1968) estimated that approximately 0.05% of pink shrimp *P. duorarum* in the Gulf of Mexico survive 35 days from hatching to postlarval settlement to nurseries. Somers unpublished (1993) pooled all larval samplings in the gulf of Carpentaria to estimate survival following the method developed by Munro et. al (1968). Somers (personal communication) estimated that survival rates using catch rates and the midpoint of the duration of stages using the method adapted by Munro et. al (1968), Somers estimated that survival between zoea and postlarvae was 4.85% or 22.02% per week which over a period of 3 weeks represents a survival rate of 1%.

(b) *Larval diurnal behaviour*

Sampling of diurnal larval patterns was carried out over a 28 hour period using square set nets (30*30 cm and 250 micron mesh) attached to frames constructed from stainless steel tube 30 *30 cm. Nets were positioned at three depth strata (0.5, 10 and 20 metres) and the method adapted from Staples (1979). The nets were recovered after 15 minutes over each hour from 1200 hr 20/1/93 to 0200 hr 21/2/93 and samples were preserved in 5% buffered formal sea water for subsequent laboratory sorting. Within the mouth of each net a flowmeter was mounted to enable volume filtered to be estimated. A model of real time illuminance was developed following advice from the Department of Astrophysics, Adelaide University and information obtained from the Astrological Society, South Australia.

The main objective of the study was to obtain information which would allow diurnal patterns to be modelled and related to illuminance. Because of manpower limitations and shortfall in funding required the sorting and identification was not completed.

7.4 Laboratory methods

(a) *Subsampling and sorting.*

Following advice from C.Jackson (CSIRO, Cleveland) a 27 cm Folsom Plankton splitter was acquired from CSIRO and the design adapted by Menzel Plastics, Adelaide. Gear constructed using the diagrams and specifications in the literature (including Folsom splitters) proved unreliable, (see Guelpen et. al 1982). Initial tests on number within subsamples (3) indicated small variance within samples compared to variation between samples and therefore only one subsample was used for Folsom splits ranging from a quarter to a sixteenth depending on sample size. Also, significant differences between subsample sizes of 1/16 to 1/8 were not detected but it was apparent that splits exceeding 1/32 were more likely to be less reliable and biased. The CSIRO designed Folsom splitter proved reliable and accurate and usually a 1/16 of sample was used for consistency. A detailed study of sub sampling was discontinued as this proved to be a major study and was beyond the manpower capability of the project.

A major problem was the large number of larvae and large amount of dead epiphyte material and other algae in the December -February periods. Glass sorting trays were modified from equipment borrowed from CSIRO with sorting undertaken using Wild/Leitz stereo microscopes fitted with 1.5 objectives. Final identification and counting was undertaken using a Wild M3Z Kombistereo microscope using a magnification range of 60-200 X for secondary separation and up to 250 X for final identification and counting. Small aliquots of sub-samples were pipetted onto glass sorting trays and examined with the aid of fine stainless steel needles mounted in glass rods and fine tweezers. Larvae were transferred to small vials for final identification using higher magnification.

Subsamples required 3-30 hours to sort depending on amount of algae, other animals and numbers of prawn larvae. Approximately 100 prawns could be identified in 1 to 3 hours with numbers in sub samples ranging from 0-1,000 individuals. Initially, sorting and identification was exceedingly slow but sped and accuracy increased with experience and training.

(b) Identification

Identification was a difficult task and the expertise of Chris Jackson (CSIRO) was acquired for a week to train personal and improve methods prior to the main sampling study. Training was aided by a cultured collection of larval stages of *P. latisculcatus* and *Metapeneopsis palmensis* which were mounted on microscope slides. Image analysis was used to build computer images from a reference collection and these in turn were used to train personal in sorting and separating specimens based on clearly defined attributes. Literature on Penaeid systematics was summarised and images taken of diagrams and used as a further tool in training personal and maintaining skill. The main literature used in systematics were Jackson (1986), Hudinaga (1942), Shokita (1984), Fielder et. al (1975), Morris and Bennett(1952), Jackson et. al (1989), Young (1977), Kirkegaard (1972), Dakin and Colefax(1940) and Paulinose (1973). A general diagram of metamorphic stages from eggs to post larvae is illustrated in Appendix 4.3

7.5 Results

(a) Larval identification

The guidance and advice provided by C.Jackson enabled a clear set of diagnostic features to be used to separate larval stages of both species. The features used to separate larval stages needed to be readily identifiable and common to the particular species.

There are likely to be two species of the genus *Metapenaeopsis* in samples.

(i) Naupliar

This is the first larval stage in development. Nauplii are frequently smaller than 250 micron and many would escape through the 250 micron net. The larvae at this stage are nearly impossible to separate species because of no clear differentiation in development. The numbers in some samples were "enormous" and sorting and identification of nauplii was not undertaken because of these problems.

(ii) Zoea stages

The main features of species discrimination for zoea lies in the setal formula of the endopod on the second antenna. One setae is positioned at the anterior margin of the protopod. Two more setae are positioned terminally on the first segment of the endopod. In *P. latisculcatus* there is also one setae in the middle of the first endopodal segment whereas for all *Metapeneopsis* spp. specimens this point has two setae.

The Zoea 1 stage.
This is characterised by three main body parts -body, antenna and posterior portion. Important characteristics are:

- the disc shaped body is covered by a carapace. The unstalked compound eyes are visible beneath the carapace along with a naupliar eye which appears as a small dark spot between the where the eyes will emerge;

- there are 2 sets of antennae. The first antenna is composed of three major segments; the second antenna consists of a protopod (base portion) of three segments, plus an endopod and an exopod of two and nine segments, respectively.

- the posterior portion at this stage of development shows sign of segmentation and the cleaved telson bears 14 setae and no uropods.

The Zoea 2 stage.
As the larvae develops from zoea 1 to 2 stage numerous changes occur in respect to segmentation of the antenna and the posterior portion. The changes are small and difficult to distinguish. A major and obvious change used was the overall increase in size and the emergence of the stalked compound eyes from beneath the carapace. The same antennal setal formula for zoea 1 to 3 is used to discriminate between species.

The Zoea 3 stage.
The main distinguishing feature of this stage is the appearance of biamous, setose uropods near the telson. At this stage, the telson becomes distinct from the sixth abdominal segment of the posterior portion.

(iii) Mysis stages
The three mysis stages are visibly quite different and readily distinguished from the zoea stages. The larvae at this stage more closely resemble adults than previous stages. The first and second antennae are no longer used for locomotion and now have an appearance similar to the adult antennae. The pleopods and pereopods are distinctive and increase at each stage. The carapace fits more closely to the thorax and the rostrum becomes more obvious and begins to extend past the eyes. The telson elongates and becomes less tapered.

For all three mysis stages the main feature used to distinguish between the two Penaeid species was the number of spines present on the telson. *P. latisculcatus* has 16 spines (8 on each side of the telson) while in *Metapeneopsis* spp. there are 14 spines (7 on each side of the telson). As in the zoea stage the myses of *Metapeneopsis* are smaller, compact and have shorter antennae compared to *P. latisulcatus*. The simplest feature used to distinguish between the 3 stages of mysis development is the gradual increase in size of pleopods.

Mysis 1 stage.
The first 5 abdominal segments contain only the buds of the newly developing pleopods.

Mysis 2 stage.
The buds are now clearly differentiated into two segmented pleopods.

Mysis 3 stage.
Now the two segments of the pleopods become elongated and have two terminal setae.

(iv) Postlarval stage.
This stage is easily separated but discrimination between *P. latisculcatus* and *Metapenaeopsis* spp. was somewhat difficult and this was a major obstacle in separating both plankton and nursery net samples when settlement is high. The telson and pleopods are the main characters for separation from myses The pleopods are very large and setose and the telson becomes strait and narrow, (see Kirkeegard 1972 and Jackson et. al 1978). The colour, ventral spines on rostrum, spots or hairs on the last tail segment should not be used in separating species.

The main character used should be the telson based on fixed and moveable spines and formula. Another feature characteristic of larger *Metapenaeopsis spp.* post larvae is the appearance of a dorsal ridge on the 3rd tail segment and the pterygostominal spine situated ventral to the eye.

(b) *Distribution and abundance*

(i) Differences in abundance of *P. latisculcatus* and *Metapenaeopsis spp.*

Larval numbers were highly heteroscadistic and data required transformation (log number +1). Data were subjected to a ANOVA based on testing Species(S)*Year(Y)*Month(M) *Transect(T)*Aspect(A) with orthogonal polynomial trends tested for Month. The effects and contrasts were evaluated and homogeneity of variances tested using Bartlet's test. Residual and normal and half normal plots were used to examine the effect of transformations. ANOVA used number and log number (logn) with incorporation of temperature and salinity as covariates. Analyses were also restricted to species and year. Larvae were either pooled (all stages)or analysed as a factor (ie Stage, 3 levels).

The analysis and interpretation are not trivial because of heteroscadisticity, change in error and were constrained by missing treatments and values. Other statistical tests undertaken were:

. normal tests based on Anderson-Darling and Watson tests;
. half normal and normal plots of residuals;
. bootstrap resampling methods.

(ii) Trends in abundance of *P. latisculcatus* and *Metapenaeopsis spp.*

The three larval stages were pooled for samplings taken from November to March over 1992/93 and 1993/94 to compare distribution of both species.

For number of larvae Bartlet's test showed that variances were not homogenous (Chi-sq 946.7, df 19) with exceedingly high variances within Transects ie big differences in stations at certain periods.

All main effects using number (ie not transformed) were significant with a strong quadratic trend of Month indicting strong seasonal effect. However, first order interactions were significant as were all second order interactions except S*T*A. For using log n there was no significant difference between species numbers and all other main effects and interactions except S*A, S*Y*M, *Y*T, S*Y*A, S*M*A, Y*M*A, S*T*A were significant ($p<0.05$).

The mean numbers of *P. latisulcatus* and *Metapenaeopsis spp.* over all treatments was 239 and 115, respectively. The difference was significant (sed 45.2, $p<0.05$) indicating that there are more larval *P. latisculcatus* in the region than *Metapenaeopsis spp.* but using log n no significant difference was apparent, see Figure 32.

The significant interactions are important. The S*Y indicated that there were proportionally more *Metapenaeopsis spp.* in 93/94 than 92/93 which was a different "pattern" (response) to *P. latisulcatus* density in 1992/93. On the basis of this preliminary analysis using un transformed data there would appear to be about 2.5 times more *P. latisulcatus* in 1992/93 than 93/94. The numerical abundance of *Metapenaeopsis spp.* larvae indicates that it would be a potential competitor if the resource (eg. food) is in short supply.

There was a substantially larger difference (451 v 27) in *P. latisulcatus* between Transects with larger numbers in Transect 1 than Transect 4, however, the difference (172 v 57) in *Metapenaeopsis spp.* between transects was less but still significant (sed 63.9).

The S*Y*M effects are most relevant. For *P. latisulcatus,* highest density in 1992/93 occurred in January while in 1993/94 peak numbers occurred in December, Figure 33. For *Metapenaeopsis spp.* highest numbers occurred in January of both Years.

Generally there were more *P. latisulcatus* and *Metapenaeopsis spp.* in the mid gulf regions of all Transects except for the high numbers in the east in January 93.

The log transformation (log n) was considered more appropriate and showed that there were more *Penaeus latisulcatus* and *Metapenaeopsis spp.* in the middle of the Gulf than the sides (S*A effects) with a larger number of *Metapenaeopsis spp.* occurring on the west side compared to *Penaeus latisulcatus.* The S*M*T interaction was not significant ($p = 0.066$) using log n with the highest mean, *Penaeus latisulcatus* occurring in January while in 1993/94 the highest mean occurred in December. For *Metapenaeopsis spp.* the highest means occurred in January of both years. The S*Y*T interaction was not significant ($p = 0.777$) with more larvae occurring in Transect 1 than 4 over both years. There were a larger proportion of *Metapenaeopsis spp.* in the south (ie. Transect 4).

Salinity and temperature alone or in combination over Transect had no significant effect due to large variance in numbers and the dominance of the Transect and Aspect effect. There was tendency for numbers to increase with temperature and decrease with salinity. It is evident that larvae occur mainly in a hypersaline environment, which is inconsistent with Penn's (1980) results in Shark Bay , Western Australia.

By restricting analysis to P. latisulcatus, the covariates had no significant effect on numbers over Transect but when analysis was restricted to Transect 1 the effect of salinity was highly significant ($p<0.009$), suggesting that early larvae (zoea, myses) have preference for high salinity which may be an explanation for the distribution patterns detailed above. Salinity may be one of many important "cues" for early larval dispersal. For epibenthic post larvae, high settlement (and sometimes highest) occurred on the western side where salinities are lower, suggesting that post-larvae may have less preference for settlement to habitats of greater salinity.

(iii) Analysis of *P. latisculcatus* larval numbers in 1992/93

The analysis of all larval stages (zoea to post larvae) was analysed by an ANOVA incorporating polynomial trends from October 1992 to March 1993 over Transects 4. All main effects and interactions were significant. There was a highly significant quadratic effect in Month and quadratic interaction in Month*Transect. However, there was strong influence of station or Region on residual patterns, owing to skew and frequent zero values at periods of high densities (see below).

Results indicated that numbers were low in October, peak in December, then decline with more larvae in Transect 1 than Transect 4 and in the mid region. However, the response is not consistent over time (M*T interaction) or Aspect(M*A). The three way interaction M*T*A suggests that there are fewer larvae in the eastern side of the southern area compared with the west, but the opposite pattern occurs in the top of the Gulf (Transect 1). There was indication of a bimodal distribution of larvae (zoea, mysis and post larvae) in Time for Transect 4 with a peak in November and January.

Analysis of zoea 1 and 2 numbers were regarded as independent, since sampling intervals were 25-30 days apart and it was unlikely that the interval between spawning and sampling would exceed 7 days. Analysis was restricted to middle stations (Transect 3) from each of Transect 1 and 2. The restriction reduced skew, variance, change and the frequency of zero counts in periods of high settlement. Figure 33.1 illustrates seasonal trends in larval numbers of Transect 1 and Transect 4 from October 1992 to April 1993.

Mean numbers (log transformed) of zoea have two well defined peaks in Transect 4, with the first occurring in December 1992 and the second in February 1993. From November to January, mean number of zoea were significantly ($p<0.05$) larger at Transect 1 than 4, whereas in March the mean number was significantly ($p<0.0005$) higher at Transect 4. There was no significant difference in means between Transects in February and both Transects had zero values in October 1992 and April 1993 indicating that spawning was restricted to the period November to March. Appendix 6 details polynomial tests for trends for combined and separate Transects. It is evident that there is a highly significant ($p<0.001$) cubic effect in Time for Transect 4, (see Appendix 5).

Nonlinear modelling for fits to each Transect are illustrated in Figure 33.2. For Transect 4, the double fourier model was highly significant ($p<0.001$) and the best fit to data, see Appendices 6 & 7. The gaussian model did not converge for Transect 4 as would be expected by the plot of data. The analyses clearly indicate that zoea distribution is not gaussian with indication of two peaks early zoea supporting the hypothesis that two spawnings occur.

Larval numbers were significantly higher at Transect 1 at an earlier period than Transect 4, indicating that either earlier spawning and/or higher egg production occurs in the northern part of the Spencer Gulf compared to the south. The peaks in larval numbers appear to have phase differences, with numbers at Transect 4 lagged by approximately one lunar phase. Peak numbers occurred at day 100 at Transect 1, while in Transect 4 the largest peak occurs some 25 days later, suggesting geographical differences in egg production and spawning.

The northern waters of Spencer Gulf are a most important habitat for prawn larvae and effluent discharge into the gulf over the period November to February should be kept to a minimum level, especially in the vicinity of Whyalla to Port Pirie.

(iv) Trends in Temperature and Salinity and association with distribution

Temperature and salinity were subjected to ANCOVA using polynomial trends for Month with the model consisting of the following treatment Year(Y)*POL(Month;3)*Transect(T)*Aspect(A). Residual patterns and Bartlet's test indicated that data did not require transformation. Trends in temperature are detailed in Figure 34.1. The grand mean from November to March was 21.07° C and temperatures were significantly ($P<0.005$, sed 0.014) warmer in 1992/93 (21.14° C) than 1993/94 (21.00°C).

However, the seasonal response was not consistent between years (Y*M) with temperatures being significantly colder in November and December 1992 than 1993, but response increased largely from December 1992 to January 1993 and remained higher than 1994.

A highly significant ($p<0.002$) linear-quadratic trend in temperature occurred over Month and there was a significant ($p<0.002$) M*Y interaction. In 1992/93 peak temperature (22.79° C) occurred in January. Mean temperature was highest (22.35° C) in February. Water temperatures were significantly higher in Transect 1 than Transect 4 with temperatures increasing from east to west. The T*A interaction was not significant.

There was a large difference in temperature across the Gulf (Aspect) with increasing trend from east to west, however, the Y*M*A interaction was significant indicating different responses. Highest temperature occurred in January 1993 at the western side (T1) with a mean value of 23.4 ° C. High temperatures from mid December to early February are expected to be more favourable for survival as the planktonic stage would be reduced.

All salinity main effects and interactions were significant ($p<0.05$). The grand mean was 38.47 ppt clearly indicating the hypersaline nature of the Gulf. Salinity was higher in 1992/93 compared to 1993/94 with a highly significant ($p<0.001$) linear (increasing) trend from November to March.

The mean salinity at the top of the Gulf was 40.01 ppt while in the south it was 36.94 ppt, with salinity increasing from east to west proving further evidence of flow up the east and down the west side of the Gulf.

Salinity were lower over all months of 1992/93 compared to 1993/94 which contrasts with the annual trends in temperature. Temperatures on average are colder on the east side of the gulf and warmer on the west, which may be attributable to water circulation patterns, (of colder less saline water moving along shore up the west side and movement of warmer more saline water down the east side with a certain (unknown) degree of mixed water in the middle of the gulf). It is therefore plausible that long shore drift may be another mechanism whereby larvae are advected to the northern area of the Gulf.

(v) Trends in *P. latisulcatus* larval stage numbers from December to March over 1992/93 and 1993/94.

Data were highly skewed requiring log transformation for treatments Year(2) Month(4)*Transect(2)*Aspect(3)*Stage(3). For both years the numbers of larvae were 270, 10, 1 m^3 for zoea, mysis and post larvae, respectively clearly indicating the dominance of the zoea stage in samples. The results indicate large difference in numbers of zoea and myses between years with 1992/93, having 1.6 and 2.8 times the numbers compared to 1993/94.

Peaks in zoea numbers over each month differed between years, see Figure 34.2. The numbers of postlarvae were low everywhere, but the highest proportion occurred at Transect 4 in February which may be attributable to a net southward trend in dispersal resulting in substantial waste of larvae. Furthermore, there were more postlarvae on the sides of the Gulf than the middle suggesting dispersal of early larvae up the middle of the Gulf and spread of postlarvae to the sides.

There were more postlarvae on the eastern side of the gulf in Transect 1 while in Transect 4 there were more on the western side.

The different pattern in response (or change) in larval numbers was consistent between Years with numbers increasing in Transect 4 and decreasing in Transect 1 from January to February. This change (or interaction) was associated with a larger proportion of postlarvae in Transect 4 in February.

It is hypothesised that the patterns are attributable to either advection southwards from mid January to February and/or to different spawning patterns between northern and southern sub-populations. If due to advection, then there would be substantial waste of larvae or egg production indicating that fishing from mid February may be a means of offsetting effort on pre spawning and spawning subpopulations from November to December. However, this remains to be proven because the reproductive viability and spawning sequences need to be verified by further work.

(c) Larval survival

The mortality rates estimated from relative abundance data from sampling from December 1992-March 1993 were estimated by a similar method used by Munro et. al (1968). Relative abundance of each stage were divided by duration of stage (midpoints) and mortality estimated. Table 7 provides detail of mortality estimates using a mid point interval of 7.5 days, zoea to mysis and 12 days from mysis to postlarvae based on average duration of *P. japonicus* cultured at 18-21°C determined from literature. Average mortality from zoea to mysis was 0.266 and from mysis to post larvae 0.062 per day.

The results are consistent with the work of Munro et. al (1968) who estimated a survival of approximately 20% per day for *P.duorarum* in the Gulf of Mexico. Further work on survival using a larger data set and different analytical methods is being and will be reported elsewhere. The survival estimates were provided to Prof. J. Noye for use as decay parameters for a 3-D advection-diffusion model of larval dispersal. Further, information was on the expected ranges of the length of larval life, spawning patterns based on maturity and detailed egg production density profiles were provided to J. Noye to allow a dispersal model to be developed. Model predictions were planned to be tested by empirical field data (i.e. settlement in nurseries) by the author in association with a biometrician. Information on larval distribution patterns across northern and southern Transects and along the middle regions of the Gulf of each transect was also provided to Prof. J. Noye.

7.6 Discussion

The results of the work support the main management strategies adapted since 1988, ie. maintain a reproductive buffer in the north (and Cowell) and control the spatial exploitation over the reproductive period (October to March), especially in the northern region of Spencer Gulf. There are two spawnings which are reflected in dfourier trends in larval distribution. The main spawning which contributes most egg production occurs in the period January to February. The spatial differences in early larval distribution are likely to reflect or mirror local egg production and advective processes.

Substantially higher numbers of larvae occur in the northern part of the Gulf, except in March, which may be the result of advection. Spawning, as reflected in early zoea numbers, appears to occur for a longer period of time in the southern area, with more spawning taking place in March compared to another part of the Gulf. From modelling currents, one would expect the larvae from early spawnings (November to January) to be advected to the north, with a general increasing trend in numbers of settlers up the Gulf on the assumption of no habitat settlement preference. However, strong quadratic site effects in latitude occur on the Western side of the Gulf, suggesting that local egg production, nursery habitat and advection are important processes affecting settlement to nurseries (see below).

Modelling settlement, using general information on population fecundity, spawning and oceanographic data (tidal currents, wind, etc) is unlikely to be a valuable tool for real time management. Evidence clearly indicates that the model structure and the input required needs to incorporate different patterns in egg production, habitat preference and long shore drift, and differences in larval survival between spawnings. Generally, the advection diffusion model cannot capture the real life dynamic complexity and could generate chaos. Greater resolution of, and incorporation of, realistic input data would be cost-prohibitive and would not be a worthwhile tool for real time management. The advection diffusion model developed by Noye and Nixon may not provide reliable representation as to what occurs in the real world.

8. POSTLARVAL SETTLEMENT PATTERNS, JUVENILE DISTRIBUTION AND SURVIVAL

8.1 Background and objectives of the study

Major differences in spawning patterns of *P. latisculcatus* between different geographical areas have been identified. It is expected that annual settlement pattern, growth, survival and emigration may vary owing to egg production differences and environmental characteristics of nurseries. Garcia (1972, 1977, 1988) and Garcia and Le Reste (1981) provide detailed accounts and review of inter-relationships between life history stages of Penaeids. Young (1977) and Young and Carpenter (1977) provide detail of an excellent study of postlarval distribution of Penaeids in Morton Bay. Substantial work has been undertaken on prawns in the Northern prawn fishery since 1963 due to the initiatives of S. Hynd and I. Monroe (see CSIRO reports). Hill (1987) provides an account of more recent studies in northern Australia including the excellent work undertaken on the larval ecology (see above), population biology of juvenile prawns in the Gulf of Carpentaria, Staples (1979,1980a, 1980b), Staples and Vance (1979, 1985, 1987) Staples et. al (1985), Loneragan (1994), Reproductive Biology by Crocos (1985, 1987 a, b), and Crocos and Kerr (1983, 1986). Few studies of sub tropical Penaeids have been documented and the work of Potter et. al (1991) in Western Australia and O'Brien (1994) in Moreton Bay are most relevant.

Except for CSIRO, little fundamental research has focused on simultaneous study on different facets of the prawn life cycle in order to determine factors which effect recruitment to the fisheries. A major problem of all work relating to postlarvae/juveniles studies relates to the efficiency of sampling gear and catchability differences between moon phase, season and habitat attributable to prawn behaviour of different species.

Background studies in Spencer Gulf have shown that their are two recruitment pulses to the grounds. The main one which occurs in February was assumed to be derived from over wintered recruits, while the June recruitment to the grounds was considered to result from early settlement pulses (December/January/early February). A number of hypotheses have been put forward to explain the two recruitment patterns to the grounds and to test assumptions which have significant management implications:

1. Early spawning produces early recruits which grow rapidly and recruit to the grounds in May/June (ie. a resident time of 3-4 months, attain a size of 23-25 mm CL in June, and are 30-34 mm by February (Year +1 i.e. age 12-13 months).

2. Settlers from early spawning have a resident time of 3-4 months and grow fast resulting in a size of 28-30 mm CL on grounds by June (ie. age 5-6 months).

3. Late spawning generates a recruitment peak in early to mid March and prawns overwinter and either:

    - grow to approximately 11 CL mm by mid November, then grow rapidly from November to mid February (1.5-2.0 mm week) to reach a size of 28 -30 mm CL by mid February (age 11 months on grounds and resident time approximately 9 months in nursery);

    - grow to approximately 11 mm by mid November and grow more slowly (1.0-1.5 mm week) to reach a mean size of 25-26 mm CL by mid February (age 11 months) and size 30 -31mm by June;

    - grow to approximately 11 mm in mid November with growth rates of (1.0-0.5 week) to reach a size of 24mm by February (age 11 months), 28 mm by April (13 months), 31 mm CL by June (age 15 months) and attain a size of 36 mm CL in February Yr 2 (age 23 months).

The purpose of the work was to consider how events in nurseries affect adult prawn populations and to link larval field and modelling studies to provide an understanding of how larval dispersal may affect recruitment patterns to the fishery. Long term time series of data are needed to draw relationships between recruitment to nurseries and recruitment to fisheries and is beyond the scope of the study.

A major purpose of the work was to develop methods for long term stock assessment which requires an understanding of the fundamental factors affecting distribution and abundance of different life history stages. It is pointed out that a key word is spatial. Drawing inference on restricted spatial sampling, even though there is high level of statistical power, may be misleading and not capture important features structuring recruitment to the fishery.

Limited spatial sampling of postlarvae/juveniles may be a waste of manpower and funds. This may be relevant to a number of conclusions reached by workers where postulations are based on small scale spatial sampling, yet direct relationship to large systems is inferred. Making inference to a global scale from small scale spatial sampling is a major biological and statistical problem herein termed "pseudo-representation " (c.f. pseudo replication, Hurlbert, (1984).

The objectives of the study were:

(a) to develop efficient gear for sampling postlarval and juvenile populations which would eliminate differences in catchability associated with season and tide;

(b) to determine seasonal recruitment patterns to nurseries and trends in latitude and Aspect;

(c) to determine whether differences occur in abundance and size occur across nursery habitats;

(d) to determine seasonal patterns in emigration and residence time in nurseries;

(e) to determine main nurseries and habitat characteristics over broad spatial scale over each side of the Gulf;

(f) to determine growth patterns ;

(g) to determine differences in survival and test whether initial density is associated with higher mortality;

(h) to model water temperature and compare longterm trends in air temperature;

(i) to determine "best" sampling plans for longterm assessment of juvenile populations;

(j) to determine whether population levels in nurseries are reflected by larval numbers and to determine relationship between settlement and recruitment to the grounds;

(k) to determine whether sampling plans can be "optimised" and used for assessment of man made impacts on prawn nursery habitats;

(l) to obtain information to allow the feasibility and cost benefits of restocking to be assessed.

8.2 Post-larval sampling methods

(a) Sampling gear.

The western king prawn is nocturnal and activity or emergence from substrate effected by light intensity and water temperature. During winter catchability of conventional beam trawls is largely effected (personal observation) and different efficiencies may occur during a season owing to a combination of factors including: *light intensity, temperature, patchiness on surface and difficulty in sampling the water column.* The latter is important as it is difficult to sample the complete water column consistently due to limits on beam height and constraints of depth and rapid depth changes occurring with tide. Most importantly, night time operations are less efficient than daytime. In order to overcome the catchability problem and the need to develop an efficient sampling device, a number of tests were undertaken using different gear. A electric beam trawl was developed with the assistance of ETSA engineers (Port Augusta) but this proved unreliable and dangerous.

A "jet net" or a beam trawl fitted with a water pump was developed which was based on modification of nets used to harvest *P. japonicus* from the MTA prawn farm in Japan (personal observation, (see Lewis and Carrick, 1987). Numerous tests of the jet sledge were undertaken over 1991/92 at three regions for the specific purpose to reduce sediment load and maintain sampling efficiency because of the strenuous work involved in handling the gear and in sorting.

Devices and methods used to increase efficiency and reduce load were :

- fitting the sledge with a rake (12 cm spikes separated from 5-10 cm and penetrating substrate from 5-8 cm) which was set at different angles of incline to bottom, different tickler chains situated in front of the water jets and most importantly the volume pumped and distance of jets from substrate.

Two types of net were tested a cone with rectangular codend and a panelled with rectangular codend. In both nets a standard 2mm nylon square mesh was used and the cone type was adapted due to greater turbulence and easier washing of catch. The frame of the sledge was constructed from 24 cm (OD) steel tubing and galvanised after construction. The beam consisted of a path width of 85 cm (internal distance between frame) and was constructed from 4*4 cm galvanised iron with skids constructed of 10 cm*0.5cm plate with 1cm marine plywood mounted on the bottom of skids. The water jet system was powered by a 5.5 HP Honda petrol engine with a Finsbury centrifugal pump with capacity of 500 litres per minute. Field sampling tests and diving observations indicted that a volume of 300 litres per minute was an optimum pump rate and the control throttle was marked to ensure consistency of pumping.

Testing of pump performance was routinely undertaken before each sampling using a 60 litre container. A 't-bar" section of galvanised pipe mounted on the base of the beam was attached to a 30 cm internal diameter rubber hose which joined the pump. The 't-bar" was 85 cm wide with 2.5mm holes placed at 50 cm distances along the pipe which produced strong water jets when pumping at 300 litre per minute. The "t-bar" or jet system was inclined at an angle of approximately 30 degrees to base (ie bottom) and situated at 30 cm from the skid base to allow maximum pumping or disturbance effect on substrate.

The vessel was fitted with two 2.5 metre *10 cm diameter aluminium outriggers with the net towed on one side and balanced on the other using a 1metre parachute drogue. The outrigger enabled to net to be towed with minimal disturbance from propeller wash. Diving observations and examination at low tide indicated that the net induced a substantial disturbance path penetrating 4-5 cm. Preliminary, observations undertaken of efficiency by re sampling narrow 100 metre * 2 metre grids marked by buoys attached to star droppers and laid out with a float line.

The previous path of the net was easily seen and resampling tracked the paths. Preliminary results indicated that the gear efficiency ranged from 90-98% which was high but not surprising as the water jet and tickler induce high disturbance and resampling was easily tracked owing to the observable path of the net. On the basis of results it is assumed that the gear is maximally efficient and that net efficiency is constant between season and that a weighting factor is not required to estimate abundance. It is noted that sub adult *P. latisculcatus* (20 -25mm CL) in aquaria (water temperature 14° C) at the Noarlunga aquaculture facility did not bury more than 2-3 cm below surface (personal observation) and it is likely that juveniles would not bury deeper.

The optimum trawl speed was 2.7 minutes over 100 metres using 70 HP Johnson outboard with a 20 cm propeller at 1300-1500 rpm depending on tide, wind and sediment load. The "jet-net" is in fact a dredge which initially posed enormous handling and sorting problems which were rectified by different sieving and washing methods and innovations. Tests using a 1mm square mesh codend resulted in substantial sediment "build-up" and sampling proved virtually impossible in some substrates due to insufficient sieving-out of sand/mud particles and shell. However, the 2 mm mesh largely reduced the sieving problem and was manageable over all types of substrate. There was a considerable amount of trial tests to handle gear, sieve substrate and a small electric winch powered by a 12 Volt battery unit and an aluminium roller made the work less strenuous and more efficient.

(b) Identification and measurement of size and development of a database system.

Identification and separation of small postlarval *P. latisculactus* from *Metapenaeopsis sp.* proved difficult owing to inconsistency in a number of diagnostic features between the two species and the large numbers in samples. Main literature used for constructing a working key were based on literature (Dall 1957, Racek 1959, Racek 1968, Racek and Dall 1965, Young 1977, Grey et. al 1983, and Jackson et. al 1989), among others. The determination of key attributes over a wide size range using image analysis was used as a reference and tool for identification.

The most consistent taxonomic feature used to separate *P. latisculcatus* was the presence of 3 moveable spines on telson. It is noted that the absence of hairs on the last tail segment and melanophore "spots" should not be used as diagnostic features as *Metapanaeopsis sp.* has been found with "spots". Also, "hairs" have been found on the last tail segment (abdominal somite) in some P. latisculcatus. The presence of a pterygial spine beneath the eye while useful in larger individuals is not a clear feature in small specimens. The stryadulating organ characteristic of *Metapenaeopsis spp.* is not always present and the presence of a ventral spines in rostrum is an inconsistent characteristic. Identification was undertaken using Wild M5 microscope and the carapace measured using an ocular vernier eyepiece. An innovative device to assist in large scale measuring was constructed by Menzel plastics which facilitated and increased measurement efficiency.

A data base system was developed which included:

- a log of field information;
- a sorting and counting log;
- a measurement log.

All three files were matched and information validated with programmable procedures written in DATAFLEX and FOCUS for summarising and manipulating data files. The system required substantial development in conjunction with a data base programmer. Initially, a database system was set up using MINITAB but this proved too cumbersome in linking files and monitoring progress. It took a considerable amount of time to develop, test and enhance the DATAFLEX/FOCUS system.

(c) Sampling plans

Sampling was based on a fixed effects philosophy with sampling locations strategically spread over latitude including both sides (aspect) of the Gulf, see Figure 35. The width of each Site was measured using a calibrated 100 metre rope, staffs and hand bearing compass. Attempts to measure slope using a levels proved far too time consuming because of physical constraints imposed by mud and were abandoned. Relocation of sampling sites was assisted by portable GPS (Furuno, Model T2A) provided by industry. Initially, over 1992 sampling tested the variation of replicates (2) within sub-plots over each strata within 8 sites. Variance was small compared to variation between sub-plots and 2 adjacent replicates within a sub-sub plots could be considered as pseudo-replicates. The refinement in sampling allowed larger spatial treatments and a further vessel was acquired by industry (2) to allow simultaneous sampling over the region at consistent time periods. That is, only one shot was done within each subplot and the number of sampling sites increased. The main study was based on 1 random haul (100 metres) within each sub-plot of each strata. The sampling at each strata was based on an area of 3 (subplots)*40 *100 metres or 12,000 sq.metres, Figure 36. Hauls were randomly selected using a random number generator in MINITAB with each proceeding sampling number not selected if the same or within 3 metres in order to ensure independence. Initially, a calibrated metre rope and buoys were used to mark positions but after 12 months this was abandoned because of constraints associated with tide and increase in skill.

The sampling was based on an ANOVA/ANCOVA split plot plan for consideration of using depth, temperature, distance from shore and salinity as covariates. The plan for density comparisons included: BLOCKSTRUCTURE Subplots and TREATMENT STRUCTURE Time*Site*Strata and TREATMENT STRUCTURE Aspect*Site*Time. Other types of analyses included contrasts of Site(s) at different Times.

Other statistical techniques used in analysis included fitting periodic functions and nonlinear modelling and bootstrap resampling using procedures written by the author or acquired from NAG (Rothamstead, England) .

(d) *Modelling water temperature and air temperature*

Water temperature at juvenile sites and on grounds were modelled using periodic regression techniques and detailed results will be reported elsewhere. For simplicity only temperature summaries for False Bay nurseries and adjacent trawl grounds are dealt with in this report. A data logger for recording temperature and salinity was mounted on a beacon (14 metres) but problems with the logger due to barnacle growth and accessibility of the remote site resulted in abandoning this work.

8.3 Results

(a) *Comparisons of postlarval and juvenile densities and population structures at False Bay*

Comparisons of densities from June 1992 to October 1994 were undertaken at False Bay (latitude 33° South). The number of prawns sampled from a shot was standardised to 100 m.sq and log and square root transformations used to stabilise variance which was examined by scatter plot of residuals, and half normal scores plots, (Carrick 1980). Figure 37a illustrates mean numbers square root transformed for main effects Period, Strata and interaction (Period*Strata). Both main effects and interaction were significant which was expected.

Temperature was included as a covariate but was not significant (F=0.47, df 1, 216). Although temperature had negative effect on prawn numbers the error was high (-0.6 ± 0.82). It appears unlikely that high temperature alone can explain differences in numbers at False Bay.

Significantly ($p<0.05$) larger numbers of prawns occurred in Strata 2 (mid shore) followed by Strata 3 (offshore and deeper) and Strata 1 (inshore and shallower), Table 8. The response changes (interaction) at certain periods. For most sampling periods there are more prawns at the mid shore (Strata 2) level except for a period of high settlement at Strata 1 where numbers were largest (mean 670 per 100 m.sqr). The densities of prawns are higher than most recorded in the literature with overall means of 4.62 and 2.95 sqare metres at peak periods in 1993 and 1994, respectively.

Densities exceeded 7 m sq in some samples in 1993 following large settlement of postlarvae.

Mean numbers of prawns over each sampling period (mainly 2 weekly intervals) were fitted to smoothing splines and a strong seasonal or periodic pattern nature is evident. As illustrated in Figure 43, the numbers in 1994 did not reach the peak levels recorded in 1993. Further analysis of annual density trends (viz. 24/11/92 to 10/6/93, and 16/11/93 to 7/6/94) were undertaken by nonlinear modelling techniques with period converted to time of year (month number in fractions of year).

Density in 1992/93. A fit to a double gaussian model explained 63.66% of variance and was significant (F=14.3), (Figure 38). Fourier regression explained 60.2% of variance and was significant (F=12.5) and cubic splines (SS 12, SS 14) explained 72.2% of variance.

Density in 1993/94. A double gaussian model explained 63.7% of variance and was significant (F=6.6). Fourier regression explained 45.3% of variance and was significant (F=6.8).

Examination of scatter plots indicated that data would not be gaussian. Data were constrained from 13/12/92 (Month 0) to 21/6/93 (month 6.3) with numbers fitted to dgaussian and gaussian models. An F test was used to determine whether a significant improvement occurred by fitting the double compared to single gaussian model (see Section 6). The results indicated that the double gaussian model was a significantly better fit to the data compared to the single model, see Appendix 8. Therefore, two main peaks in settlement is substantiated by the analysis, with the first peak estimated at month 2.22 ± 0.007 and the second at month 4.12 ± 0.07. That is, the first peak is estimated at around 66 days from 13/12/92 while the second at 123 days from the initial period.

Density in 1993/94. A double gaussian model explained 44.6% of variance but was still significant (F=6.6). Fourier regression explained 45.3% of variance and was significant (F=6.8).

Stronger bimodal patterns occurred in 1992/93 and in oscillation in numbers occur in each year which are attributed to two well defined settlements. The recruitment pulses are likely to be derived from two spawning pulses within the breeding season, as explained by the highly significant d-gaussian maturity model (see above). The double gaussian model appears realistic as similar patterns were reflected in spawning (see above). It would seem that annual variation in juvenile numbers are determined by spawning patterns. (Settlement pattern and population structure at False Bay over 1994 are illustrated in Figure 37b). Strong settlement occurs from January to late March, and rapid growth and immigration occurs from January to May with the population overwintering from June to October, see Figure 38.

(b) Comparisons of the size structure of postlarval and juvenile prawns in nurseries

(i) Population structure

The size structure of prawns in nurseries was studied by pooling measurement data Strata(3) and ten sampling sites which resulted in an analysis incorporating 51,813 measurements (mm CL) for field study undertaken at comparable lunar sampling periods over 1992/93 and 1993/943. Figure 39 illustrates numbers and percentages grouped by 1mm size classes. Juvenile prawns up to 24 mm occur on nurseries and distribution is highly skewed with size classes between 3-7 mm CL comprising 69% of the population. These results are similar to those obtained by O'Brien for *P. esculentus*.

(ii) Differences in size between inshore, mid shore and offshore.

Eight sites were selected for the study which included : False Bay, Germain, Broughton, Spit, 5th Creek, Mt Young, South Cowlands and Plank Point, see Figures 31 & 40. Large differences are apparent in the size of juvenile prawns between sites. Over most sites prawns are larger in offshore Strata particularly at Germain, the Spit, Broughton, 5th Creek and Mt Young. When only site data are pooled for each strata it is evident that their are a relatively larger proportion of bigger prawns (15-19 mm CL) at the offshore zone, Figures 41 & 42.

(c) Seasonal changes in population structure, settlement and growth.

Data from 11 sites over peak settlement (3 consistent sampling periods) in 1993 and 1994 were subjected to ANCOVA incorporating tests for contrasts. Figure 43 illustrates the differences between years with indication that 1.5 times more settlement occurred in 1993 than 1994, however, an interaction occurred which was mainly attributable to the Fifth creek site where a large blue green algae bloom occurred in 1993.

(d) Latitudinal differences in settlement and annual comparisons of settlement

Latitude was included as a covariate in the analysis to determine its influence on prawn distribution patterns. Background study showed that a strong quadratic-linear trend in settlement density occurs along the western coast whereas on the eastern side numbers generally increase linearly from south to north. Data collected from geographically separated sampling Areas over 5 periods (21/1/93 to 23/3/93) and 2 Strata(inshore, midshore) were subjected to a 3 way ANOVA to test for orthogonal trends in Area or position along the coast. Figure 44 and Table 9 detail the results. All main effects and interactions were significant ($p<0.005$) with a strong quadratic effect in Area. The Area*Strata interaction showed quadratic response for Strata 2 with numbers of settlers highest at False Bay (north) and Shoalwater Pt (south). However, for Strata 1 the pattern is different ie there is a trend for numbers to largely decrease from north (False Bay) to south (Shoalwater Pt). Furthermore, the interaction Area*Period suggests that different temporal patterns in settlement occur over Area or along coast.

A wide scale survey of juvenile prawn distribution on the western side of the Gulf was undertaken, over three fortnightly periods in 1993, to determine the mainnurseries and the effect of latitude on distribution. Sampling was undertaken at the Strata level from Tumby Bay (34° 26.0' S) to False Bay (33° 0.0' S). Data were subjected to ANOVA and results detailed in Figure 44.1 and Appendix 9. The results indicate highly significant cubic-quadratics trends. Very low numbers of juvenile prawns were found in the southern areas (Tumby Bay - Arno Bay) and high numbers at Shaolwater Point (Site 12), False Bay (Site 2) and Plank Point (Site 7).

On the basis of the juvenile studies, the main nurseries identified in Spencer Gulf are situated north of 34° South. Main nurseries identified are: *False Bay, Shoal Water Point, Plankpoint, The Spit, and Port Pirie.* Generally, there appear to be larger numbers of juveniles on the Western side of the Gulf compared to the eastern side.

These results for the western side of the Gulf do not appear to be consistent with larval advection modelling predictions undertaken by J. Noye and J. Nixon (Adelaide University) and it is suggested that habitat characteristics (eg. substrate) may be another factor having influence on postlarval settlement. One could hardly expect the spatial distribution in settlement to be solely determined by currents and wind.

(e) Juvenile survival in nurseries and the effect of initial density on mortality

The survival of juveniles in nurseries was estimated over the July -November period when the population was closed (i.e. no postlarval recruitment or emigration). A detailed study was undertaken at False Bay over 1992/93 and 1993/94 and five further 5 sites were used to determine annual differences in survival on global scale. The effect of initial number on survival estimates was undertaken to examine whether mortality rate has relationship with initial abundance or density. Sampling incorporated all 3 strata (inshore, mid shore, offshore) with three independent 100 metre tows taken within each of three substrata (40*100metres) over each Strata (3) to minimise any effects of differential movement between strata.

(f) False Bay instantaneous mortality rates

The study was designed to sample over a consistent period of the year viz. from 4/6/ 92 to 22/11/92 (5.7 months) and from 10/6/93 to 16/11/93 (5.3 months). Estimates of the weekly instantaneous mortality were undertaken using log number on time. The analysis is preliminary as better GLM statistical methods are currently being used for more rigorous analysis. Data were subjected to a simple fixed effects GLM model using time (weeks) as a covariate for estimation of slopes (time nested within Strata) and testing homogeneity of slopes(time*Strata). Figures 45 & 46 illustrate the decay in numbers over time for each Strata in 1992 and 1993, respectively.

Data were logged and subjected to grouped linear regression techniques to test for parallelism of slopes. Data were found to approximate Poisson distribution and were subjected to a GLM using a Poisson Link function and tests for parallelism of slopes (Strata,Years) carried out using a procedure written by the author in GENSTAT 5.

The relationship between mortality and initial numbers was investigated by simple linear and nonlinear regression. The type of curvature (upward or down) was considered important .

For 1992 strata slopes were homogenous with F=2.08 (not significant, p=0.134), Table 10. The Strata slopes for 1992 were -0.05, -0.08, -0.06 for Strata 1, 2 & 3, respectively. The pooled strata slope was -0.064 ± 0.002 week and significant (t-value -9.08, p=0.0).

The 1993 strata slopes were homogenous with F=1.3 (ns, p=0.281), Table 11. Strata slopes were -0.02, -0.05 and -0.04 week for strata 1, 2 & 3, respectively. The pooled strata slope was -0.037± 0.002. Annual slopes were not homogenous (F=4.93, p=0.028) and 1993 had a lower mortality rate than 1992.

The Poisson Link function of the GLM proved the best statistical technique and more detailed information will be provided elsewhere. Table 12 outlines comparisons of slopes for 1992 and 1993 pooling Strata. Time series analyses were also done and information will be reported in the future.

The relationship between initial numbers of juvenile prawns and weekly instantaneous rates is illustrated in Figure 47. The regression of initial number on mortality explained 94.8% of the variance indicating that there is a strong (linear) relationship between initial number and mortality, Table 13. The curvature of the exponential was downward and the model was a good fit to data explaining about 94 % of variance. It is noted that the curvature does not increase upwards ie large exponential increase in mortality with small changes in initial numbers. Generally, the linear model best describes the relationship between initial number and mortality at False Bay and suggests that density dependent effects are likely to be important for at least that area.

(g) Broad scale trends in survival using 5 sites and overall survival

Mortality was estimated over 5 Sites *3 Strata between June and November for 1993 and 1994 using a general linear model (GLM) with all sites used as replicates. Table 14 provides a comparison of weekly instantaneous mortality between 1993 and 1994. Results indicate that substantial variation in survival can occur between years. It is evident that survival in 1993 was lower than 1994. Therefore, survival in nurseries is considered an important factor influencing recruitment to grounds. The mortality estimates from the 5 sites regarded as being more representative of the Gulf than False Bay are relatively low compared to literature, however, these estimates are based on overwintered populations and it is expected that the mortality in direct recruits would be at least double that of the overwintered recruits. Mortality varies with size and season and between years. A small change in survival in benthic postlarvae and juveniles would have large effect on recruitment to grounds.

(h) Discussion

Young (1977) found that juvenile prawn distribution was associated with the following: S-T regime, sediment, sea grass community type and geographical types. Postlarval (2-10mm CL) were found rare in depths greater than 2 metres and more prawns were found on seagrass (*Zostera sp* and *Halophila sp.*) than bare substrate in 6 sites whereas at two sites the reverse situation applied. Similarly, other species studied, *P. esculentus, M. bennettae* and *M. macleayi* were shown to have preference to seagrass than bare substrate.

Studies conducted in Spencer Gulf using different types of beam trawls including the same used by Young (1977) and Ward and Young (1982) found that postlarval and juvenile *P. latisculcatus* were found to be rare in *Posidonia sp* and *Zostera* habitats indicating that the western king prawn has preference for bare sandy/mud to muddy/sand habitats. The results clearly show that *P. latisulcatus* has preference for position on shore ie middle regions sand-mud flats. Evidence indicates that a blue-green algal (cyano-bacteria) out-burst had local effect on prawn numbers. Therefore, the discharge of nutrients, sewage and oil into the Gulf should be minimised and discharge of effluents adjacent to mangrove and sandy mud flats be more rigorously controlled and effects monitored.

The maintenance of prawn nurseries in the littoral habitats (including seagrass communities) of Moreton Bay was suggested an important factor in influencing recruitment to the fishery. It would seem that the maintenance of the sandy/mud habitats for *P. latisculcatus* is necessary for stock maintenance in South Australian prawn fisheries. Few studies of postlarval distribution of the western king prawn have been documented.

A study by Potter et. al (1991) documented the dynamics of a small population of *P. latisulcatus* in the Peel-Harvey estuary, Western Australia. It is noted that the estuary has more similarity to the Venus Bay area compared to SPG. They suggested that growth of macroalgae, *Cladophora spp.*, on nursery substrata was associated with a decline in juvenile abundance and low commercial catch of western king prawns. Potter et. al (1992) found that postlarvae (2-3mm CL) settle in nurseries from December-April and that emigration of juveniles from nurseries to the estuary occurs starts in November or December at a size <18 mm CL. They also found that movement from the estuary to inshore coastal waters begins in September at a size >20 mm CL. This contrasts to the Venus Bay area where migration from the estuary occurs at large size (>28-32) from February and reaches a peak in June. Therefore, it would seem that the Venus Bay estuary is a type of "secondary" nursery and that patterns in emigration vary across latitude and environmental conditions. As noted by Dall et. al (1990), emigration patterns are effected by interaction of environmental conditions (tide, lunar phase, temperature and salinity) and size. It is hypothesised that both size and tidal amplitude are likely factors effecting emigration patterns in *P. latisculcatus* in South Australia. The results on *P. latisulcatus* densities in SPG contrast with the relatively low numbers of tiger prawns *P. esculentus* and *P. semisulcatus* in the Gulf of Carpentaria (Vance et. al 1994, Loneragan et. al 1994), Haywood et. al (1995), and in Moreton Bay (O'Brien 1994) and for the eastern king prawn *P. plebejus* in Moreton Bay, (Young 1977).

Juvenile densities were not as high as those recorded for banana prawns by Staples and Vance (1985, 1986, 1987) in the Gulf of Carpentaria and this may be due to the smaller mesh size (1mm) used by Staples (1986) and the tendency for banana prawns to concentrate within a narrow habitat along mud bank fringes along mangrove creeks.

The net efficiency of beam trawls used for sampling tiger prawns over sea grasses in the Gulf of Carpentaria was assessed by Staples and Vance (FIRTA 82/13) who found that the gear was biased towards sampling *P. esculentus* with the net catching twice as many *P. esculentus* than *P. semisulcatus*. However, the net efficiencies were relatively low for both species (i.e. 0.35 and 0.19). Subsequent work undertaken by Loneragon et. al (1994) on *P. esculentus* using same sampling gear had efficiencies of 0.65 and 0.5 for postlarvae and juveniles, respectively. Although no differences in efficiency were detected between sites of same depth the study did not determine differences between season or depth where it is expected that efficiencies may differ due to behavioural changes to environment (eg. temperature) and depth (eg. differences in size). A further study by Loneragan et. al (1995) found that the efficiency of gear at low tide was estimated at 65% for postlarvae and 47% for juveniles in water less than 1 metre depth. In water greater than 1.5 metres the efficiency of the net was about 35% for juveniles.

Preliminary work undertaken in Spencer Gulf was directed to development of efficient and consistent sampling gear requiring observations of different beam trawls, electric beam trawls and a "jet net" adapted from methods used to harvest *P. japonicus* from the IMR prawn farm, Hiroshima, Japan (personal observation). Western king prawns bury during daylight. Catchability or normal trawl efficiency varies with season, however, the jet net developed at SADOF was shown to have high efficiency (95-98%) with no differences between season (summer, winter) or depth (0.6 versus 2 metres). However, the jet net developed is essentially a "dredge" resulting in substantial collection of sediment requiring considerable effort in application and in sieving and sorting. The method substantially reduces catchability and efficiency effects thereby providing an accurate tool for estimation of population parameters.

Loneragan et. al (1994) provides estimates of mean numbers of *P. esculentus* and *P. semisulcatus* over 3 sites sampled at 2 depths in the vicinity of Groote Island, Gulf of Carpentaria. The largest mean density of juveniles (ie > 3 mm CL) recorded was 18.2 per 100 m.sq ($0.2m^{-2}$). Highest numbers of juveniles occurred at shallowest depth with largest being 70 in December and all other values were less than 50 per 100 msq.

Loneragan (1995) provides results of a study carried out on juvenile tiger prawns in Albatross Bay using the same gear as Groote Island. The results generally indicate that mean relative abundance does not exceed 0.9 msq. O'Brien (1994) investigated the population dynamics of *P. esculentus* in Moreton Bay using the same gear as Loneragan (see above). The highest density was 70 per 100 msq and most values were less than 40 per 100 msq. The abundance of *P. latisulcatus* in False Bay (and many other sampled sites) in SPG appears to be at least 2-10 times higher than those estimates of tiger prawns reported by Australian workers. However there are large spatial differences in abundance of *P. latisculcatus* over latitude and even within the same location.

It appears unlikely that high temperature alone can explain differences in numbers of juvenile prawns at False Bay. However, data requires further analysis and there is a need for more long term field research and manipulative experimentation. As previously pointed out it was found that recruitment to fishery has association with air temperature at Whyalla which is situated approximately 5 nautical miles from False Bay. Substantial mortality from desiccation on nursery flats at low tide during extreme temperatures (>45 °C) or substantial exposure during negative tides and dodge tide periods may be important factors influencing survival in *P. latisulcatus.*

Large differences in settlement pattern have been reported for the same species (eg. *P. esculentus)* over different geographical areas. O'Brien (1994) found that settlement occurs from September to July with two peaks. The recruitment of *P. esculentus* is regarded as a continuous process. The first peak in settlement occurred from September to November and the second from January to April which clearly demonstrates that spawning is continuing over most of the year. Loneragan et. al (1994) reported that recruitment to nurseries was highest from October to March with the species spawning throughout the year with a peak in August/September, (Crocos, 1987).

It is noted that the highest recruitment of *P. esculentus* to seagrass beds and the time of lowest postlarval/juvenile numbers (ie May to September) are similar in studies of Moreton Bay (Young 1978, Young and Carpenter 1977; O'Brien 1994), north-eastern Gulf of Carpentaria (Vance and Staples 1992; Vance et. al 1995) and in the western part of the Gulf of Carpentaria (Loneragan et. al 1994). However, there appear to be differences in recruitment patterns to nurseries between the southern and the northern part of the Gulf of Carpentaria. Coles et. al (1985) found that peak recruitment occurs between July and December with few recruits January to April. Such differences in the timing of recruitment to nurseries are likely to be due to differences in spatial spawning and egg production and the effects of oceanic processes effecting larval dispersal and survival and settlement.

O'Brien (1994) found that highest numbers of juveniles occurred between January and June with strong settlement occurring from October to May with evidence of annual differences in patterns. Few prawns settle from June to early September and the average size at emigration was 16 mm CL (range 11.3-18.5 mm). The resident time increased as temperature declined with those settling in December (temperature approximately 27° C) having a residence time of 10 weeks (2.5 months). However, most settlement after mid-February (temperatures below 23° C) appeared to over-winter resulting in an estimated residence time of 8.5 months (emigrating in mid-December) for settlement which occurred in late March.

Modelling studies of larval dispersal in Spencer Gulf clearly indicate that different patterns in settlement could be elicited by change in wind direction (and strength), patterns in tidal flow and differences in sequences of egg production. Therefore, large variability in larval dispersal patterns and egg production are likely to effect the size and quantity of prawns recruiting to nurseries, grounds and the fishery. The size of *P. esculentus* at emigration from seagrass beds in the Gulf of Carpentaria was reported to be 10mm CL and contrasts with the larger size (10-20 mm CL) recorded by O'Brien in Moreton Bay.

The small size at emigration reported by Loneragan et. al (1994) may be due to the combined effect of high mortality and sampling method. Gear was not sampling at same efficiency in deeper water. That is, larger prawns may exist in the deeper habitats but substantial sampling would be required with the method to detect them. This would not be unexpected because high mortality would result in few numbers at larger size.

Growth rates of most Penaeid juveniles are difficult to estimate due to the effects of continuous recruitment and /or pulses of recruitment over a season, high mortality and differences in growth rates between settlement cohorts. Loneragan et. al (1995) reports a growth rate of 1mm carapace length per week for the Gulf of Carpentaria and implied a resident time of 8 weeks from settlement (2mm CL) to emigration (10 mm CL). O'Brien 1995 found that growth rates of *P. esculentus* living in a sub tropical environment (32° S) and an obviously larger periodic temperature regime had an a maximum growth rate of 2.1 mm CL in January and the growth over winter (June-August) was small (< 0.2 mm week). O'Brien found that growth rate was exponentially related to water temperature with larger growth (1 -2 mm week) occurring from 25 -28°C.

Studies of the natural mortality of benthic postlarvae and juvenile prawns are scarce in the literature. All methods reviewed (including own) suffer from a number of problems. The problems mainly related to: sampling gear and methods, the difficulty (and reliability) of separating cohorts which are constrained by gaussian fits and low numbers of larger (older) cohorts and emigration. However, the sampling gear and basic methodology appears to be suitable for population studies including estimation of annual survival differences. Stratification is required because there are differences densities and size across shore. Clearly, further field and analytical studies are required to focus research objectives and "optimise" sampling plans.

Haywood and Staples (1993) reported high mortalities for the tropical banana prawn *P. merguinensis* up to 60.9% per week with rates of 26, 38.7 and 36.9% per week for 1988, 1989 and 1990, respectively. Weekly estimates of survival obtained for *P. esculentus* in Morton Bay ranged from 5.2% to 25.2% with mean mortality rates from September-August estimated at 13.6 and 15.2% for 1988/89 and 1989/90, respectively Doi et. al (1972, Doi personal communication) working on a *P. japonicus* in the Seto sea, Japan estimated a natural mortality estimate of 0.05 week which is relatively low compared to most other Penaeids documented in the literature. *P. japonicus* displays similar nocturnal behaviour to the *P. latisulcatus* and burrows when water temperature falls. However, the low estimate may be associated with substantial reduction of local predators by man-made activities.

In the Bahai Gulf, China, fish predation on juvenile prawns was estimated to contribute over 80% of *P. chinensis* mortality in nurseries, (Li Sun, Shandong Provincial Government, Quingdao, personal communication). Substantial "predator" removal from nurseries is used to reduce predation on hatchery cultured seedling prawns in the Shandong province nurseries and this may account for the success of restocking operations (personal observation).

There are few reliable data relating to juvenile mortality and evidence presented indicates that mortality varies with size and season. From peak settlement to a period of up to 6 weeks juvenile mortality at False Bay is least 3 times higher than that recorded for over-wintering juveniles. Initially, from settlement high mortality occurs, however, mortality rate appears to decrease with size and over the winter to early summer period. Explanation of such differences in mortality are expected to be linked to predation and competition.

Table 15 provides a comparison of weekly mortality rates estimated in three other species namely *P. esculentus* in Queensland (O'Brien 1994), *P. aztecus* in the Gulf of Mexico (Minello et. al 1989) and *P. merguiensis* in the Gulf of Carpentaria (Haywood and Staples,1993). Apart from these major studies there have been few documented attempts to estimate natural mortality in Penaeid postlarval and juvenile stages using reliable sampling methods.

Edwards (1978) estimated that 90% of juvenile *P.vannamei* died over the 6-12 week period they spent in lagoons in the Gulf of Mexico and attributed high mortalities to predation by fish. The low mortality in *P. latisculcatus* may be due to a relatively low number and diversity of predators. Major predators of Penaeids (sciaenids, carangids, sparids) documented in literature have not been observed in intertidal estuaries in SPG or Venus Bay. Furthermore, sampling nurseries in day and night using a variety of gear (mesh nets, beam trawls and seine nets) indicated a low diversity and abundance of fish compared to literature for NSW, Queensland, Gulf of Carpentaria and Western Australian estuaries.

Fish observed in Spencer Gulf with substantial juvenile prawns in guts were sillaginids, pleuronectids and platycephalids (personal observation). Large numbers (greater than 20) of small (20-24 mm CL) sub adult prawns were observed in the guts of large flounder *Pseudorhombus arsius* at inshore areas in northern Spencer Gulf, (personal observation). The spatial distribution and size structure of flounder in SPG suggests that they would be a major predator on postlarval/juvenile, sub adult and small recruits to grounds, (unpublished). Trial training experiments undertaken using different baits on surface and bottom in nursery habitats in SPG, Venus Bay and West Beach indicated that most species captured had preference to small prawns compared to other baits (squid, mullet, meat). Species captured included the striped perch *Helotes sexlineatus,* tommy rough *Arripsis georgianus,* salmon trout *Arripis trutta,* yellowfin whiting *Sillago schomburgkii,* juvenile king George whiting *S. punctatus,* juvenile and adult long toothed flounder *P. arsius,* the green backed flounder *Rhombosolea tapirina* and small flathead *Platycephalus spp.* Sting rays and a skate were captured on bottom sets but showed preference to larger prawn bait compared to fish, squid and small prawns.

The American blue crab, a Portunid, *Callinectes sapidus* was reported to be a predator on prawns with about 7.6% of summer diet in larger crabs (>60 mm carapace width) consisting of prawns, Laughlin (1982). The blue crab in SPG occurs can have large abundance in both inshore nurseries and northern grounds (closed to trawling). The size structure of blue crabs taken on prawn nursery grounds for three sites is illustrated in Figure 48. Densities of blue crabs at some nursery sites exceed 0.5 m^2 (ie 50 per 100 msqr) and therefore the species may be a major predator prawns particularly when prawns are most vulnerable during moulting.

Indeed, observations in circulating tanks indicate a clear adaptation for efficient predation by the blue crab , especially on adult prawns during moulting, (personal observation). The influence of blue crab predation on prawn populations in the field is not known. However, sites with low densities of blue crabs had higher juvenile mortality than a number of sites with high densities of blue crabs (unpublished).

There may be substantial impact on postlarval prawns by a number of smaller species (eg. gobies) which occur in high numbers (greater than 1 m^2) nd a number of dense schooling species *Arripis georgianus, Hemiramphus melanochir* and whiting observed to inhabit the nurseries. Unlike Cockburn sound Western Australia, NSW and Queensland, the tailor *Pomatomus saltator* a known voracious predator of prawns does not inhabit South Australian Gulfs or West coast estuaries (personal observation). No studies have been undertaken of fish predation in south Australia except for casual observations undertaken in this study. Therefore, the impact of predators on postlarvae and juveniles remains unknown. The work of Salini et. al (1990) and Sheridan et. al (1981, personal communication) has clearly indicated that fish can have substantial impact on prawns in the Gulf of Carpentaria and in the Gulf of Mexico.

Density dependent (crowding) mortality may be an important factor in population "control" in areas where juvenile densities are high proving the resource is limited or in short supply (eg. food, space). There is a strong correlation between initial numbers of juveniles and mortality rate for False Bay suggesting that their may be limited carrying capacity. That is, as numbers of juveniles increase the mortality rate increases. However, this is only a correlation and confirmation of density dependent control requires further work including experimental field manipulation with appropriate controls, (see Underwood 1979, 1981). Density dependent mortality in nurseries is suggested to have at least local effect at False Bay. However, this does not mean that density dependent mortality "controls" recruitment to grounds. There are a number of areas in the Gulf where low densities have been observed (eg. Wood Pt, Pt Davis) at different times despite the areas being characterised as having a "perfect" nursery habitat.

It is possible that larval dispersal has major influence on distribution with some areas not obtaining sufficient supply at different times. That is, they could be considered as "vacant lots" with densities well below carrying capacity. If restocking was proven to be cost effective and feasible then the potential to enhance the "vacant lots". Possibly a broad and more even spread of postlarvae particularly to productive nurseries would result in higher recruitment to grounds than "patches" of high settlement. Obviously, current regimes and wind have a major influence on spread of postlarvae to nurseries but it does appear that postlarvae may have preference where to settle. Density dependent crowding "control" in nurseries may not be the major factor in influencing recruitment to nurseries on global scale.

Predation by fish, especially on early benthic postlarvae and small juveniles may be another important factor in structuring recruitment to the grounds by having large effect on nurseries populations. However, different levels of mortality attributable to predation and competition are likely to occur from settlement to emigration. For example, predator effect may be higher on early settlement even though strong crowding effects. That is, confounding effects are likely to occur in nurseries with predation being greater at some periods and competition higher at others.

It is apparent that there can be significant and substantial differences in annual survival of juvenile prawns which would have large effect on recruitment to the fishery. The effect of environment (eg. below average temperatures) in winter/spring and extremely high temperatures in summer may also be a factor effecting survival and this facet is being investigated over long time series using data acquired from the Department of Meteorology and recruitment (February) to the grounds.

9. SUB-ADULT POPULATIONS AND DETERMINATION OF SEASONAL EMIGRATION PATTERNS FROM NURSERIES AND RECRUITMENT PATTERNS TO GROUNDS

9.1 Objectives

The objectives were to:

- determine and validate emigration patterns to sub nurseries;
- determine and verify seasonal recruitment patterns to grounds;
- determine change in seasonal size composition and abundance.

The purpose of this segment was to validate assumptions of emigration patterns from nurseries and recruitment pattern to grounds by sampling three sites in shallow water (15-18 metres) adjacent to False Bay nurseries. Deeper water areas along the northern part of the gulf were simultaneously sampled by trawling to determine the sequences of movement from "sub-nurseries and to relate patterns with recruitment to the fishery.

The assumptions considered were:

- that two emigration patterns occur: One between December and January from overwintered recruits and another from March-May from direct recruits;

- peak recruitment to the grounds occurs in February (from over wintered recruits) and another in June from direct recruits;

- variation in patterns would have large influence on egg production as determined from size at spawning;

- variation in patterns would largely influence spatial size distribution on grounds.

9.2 Methods

Over a 3 year period strategic sites were sampled using standard trawl gear by the Ngerin and contract survey vessels using standard trawl gear by in the vicinity of False Bay (FC1, FC2, CB1, CB2) and along the northern part of the Gulf (stations 42, 27, 30, 8 & 2). Initially a codend cover (8 mm mesh) was placed over a net to determine selection and the smallest size occurring on grounds in January/February. No significant difference in the distribution of smaller prawns could be detected but larger prawns were more frequent in the codend. However, there was strong selection for *Metapenaeopsis sp.* with sizes as small as 5-12 mm CL occurring in the codend cover. The standard 4.5 cm codend cover was therefore considered to give a consistent and reliable estimate of size in *P. latisulcatus* from sizes larger than 15 mm CL and information verified that *P. latisulcatus* do not emigrate to offshore areas until at least 15 mm CL.

At each of 9 sites sampled approximately 500 prawns were sexed and measured and abundance, trawl distance and trawl time recorded. Data were scaled to abundance using a raising factor and detailed results reported elsewhere. For simplicity, actual sample numbers of male prawns were grouped into 1 mm CL size classes and pooled for all stations to enable continuous movement and growth trends to be detected as previous tagging and spatial sampling has showed that the sampling plan would capture the direction of dispersal. On an abundance scale CB1, CB2 and FC1, FC2 over 40,000 prawns were sometimes estimated from catch. Owing to the small size of prawns at three stations only one net was used and at different periods and when abundance was high the catch from one net was quartered and catch estimated.

9.3 Results

Data collected from November 92 to June 94 were subjected to Multifan plots and are illustrated in Figure 49. Smallest size prawns occurred at FC1, FC2 and CB1 in December/January and March/April and population structure indicating that growth of juveniles over December/March is greater than expected and may exceed 1.5 to 2.0 mm per week from February to March. Therefore, weekly sampling over the January /March period would be needed in order to track growth. Growth is highly seasonal in both juveniles, sub adults and adults.

Recruitment of small prawns (20 mm CL) is detected in late November and December with large scale recruitment at FC1 and FC2 detected in January (sample #3). The cohort grows rapidly from January to February reaching a size of approximately 31-32 mm CL (SAMPLE #4) as mean temperatures are high in juveniles/sub adults over this period. The February period over both years (sample #3 and #13) is dominated by a similar cohort which is spread through the northern part of the gulf, (see # 3 and # 13).

A recruitment pulse of small prawns from 19 mm CL occurs at FC1, FC2 in late March and reaches a high level of abundance by May with main recruitment only spreading to site 30 by June (see # 8). Prawns of 15mm CL were detected but were infrequent in samples indicting that either sampling gear is selective or that movement to offshore deeper grounds occurs at larger size (19-20 mm CL). Similar trends were detected from December 93 to June 94 with recruitment of small prawns occurring in FC1 in December with a large pulse in January followed by large scale recruitment to grounds in February with the cohort completely dominating the population with wider spread, (cf. June). In mid March 94 another wave of small prawns is detected at FC1 and FC2 which recruits to grounds in December. Similarly, the spatial spread is limited when compared with the February recruitment.

The February recruitment to grounds derived from over wintered recruits grows rapidly from a size of about 30 mm CL to reach a size of approximately 37 mm CL by June which is consistent to mark recapture results. The main February recruitment pulse could not contribute to egg production from December to mid January as studies have shown that most would not be reproductively mature but they may contribute to February spawning only if insemination is successful. The reproductive viability of the February recruits may not be as high as expected and the main contributors could be the June recruits and one year old February recruits plus older remnant year classes. Furthermore, early spawning (i.e. November - December) and "viable" egg production may not (as indicated from study of maturity) be derived from the June (see maturity, above). Early recruitment may be derived from the egg production of larger (older prawns).

The results have significance to derivation of relationships between spawners and recruits. There simply may not be a relationship because the "spawners" may not be reproductively viable meaning that relationships may be redundant because spawners are not being appropriately measured. This information has major relevance to stock maintenance and sustainability. **A reduction in the numbers of larger prawns at key areas could result in stock decline even though "theoretical" egg production is high and exploitation levels are "acceptable".** These matters require further investigation. Owing to spatial restrictions and spread of the June recruits it would seem that length based models used to estimate recruitment from commercial count data would be of less value than survey based length models because few of these recruits would be captured owing to small size and associated management restrictions.

10. HARVEST MODELS

Premature harvesting from February to April in the northern area of Spencer Gulf would result in substantial loss in potential value of harvestable stock. On worst case scenario, if exploitation was not controlled, it could lead to recruitment decline. In the past (pre 1981) modellers and economists advised management that fishing in Spencer Gulf should commence in February, with the optimum opening period for the entire northern area being April 1, see Sluczanowski (1980). **Therefore, past management considered the system as a global unit which implied no spatial differences in the size composition of the stock and that the system was stationary.** The models and application to management were proven incorrect in 1980 by empirical field observations at sea and simple modelling of different spatial units with more precise information on growth, mortality and movement.

It is evident that even powerful models can oversimplify a complex system and provide misleading information and predictions. Prior to 1981, the fishery was managed on the assumption that spawner recruit relationships do not occur in Penaeid fisheries which at that period was advocated by most fishery scientists and managers.

A major problem not realised by management in the past, was that of mixing of sizes and large pulse movements of smaller prawns into the grounds. Patterns have been identified over long time series using spatial data obtained from trawl surveys and monitoring the size of catch on a daily basis, and by tagging. Different regions in Spencer Gulf are monitored to determine optimal harvest periods for those areas where there are spatial differences in size over space. Harvest schedules in Spencer Gulf are developed in real time using field sampling, simple simulation, intuition and trial-and-error experiences. Uncertainty in model predictions is resolved by sampling and/or resampling just prior to fishing to "fine tune" harvest schedules and closure lines. The main objectives of real time management are:

- minimise the risk of growth and recruitment over fishing;
- maintain stable economic return (i.e. value of catch minus costs of fishing);
- minimise bycatch, by gear and harvest methods, (Carrick unpublished).

Large movement pulses of small prawns into areas open to fishing can occur resulting in substantial loss in potential biomass, egg production and value. Real time monitoring is a tool used to minimise the capture of small prawns and in some applications provide greater chance of reproduction. Price structure, prawn size, abundance, spawning sequences and egg production, mortalities and vulnerability have influence on the development of harvest schedules.

10.1 Price structure trends

Generally, Australian markets reflect price trends of main export markets except that there is a relatively larger increase in price from October to December due to increased demand. Price structure trends in local markets, and the effects of supply on price, were studied using 3 years of trade data based on frozen king prawns (cooked and green) which was obtained from the Sydney Fish Marketing authority. A data base on price by grade and quantity traded each day was used to summarise data and larger detail of results will be reported elsewhere. Data were subjected to ANOVA, ANCOVA and nonlinear modelling techniques to quantify trends in the percent increase in price from October to February using May (lowest value) as a time base over 3 years. The nonlinear exponential model while providing a good fit to data was not realistic. ANOVA was a better method of analysis and provided more detail on variation and the effect of supply on price.

Premium prices occur over the pre-Christmas period. For cooked Medium grade prawns there was an average price increase of 70% in December and there was a 90% chance that a 30-50% price increase would occur from May/June to December, see Figure 50. Information on ex-vessel prices from fishers supported the finding that price would increase by at least 30% in the November-December period from the May price base of each year. However, price can be affected by large pulses of supply to market.

10.2 Harvest simulations

Two types of harvest bivalve/trawl value simulations are outlined and are used as a tool for management - the first with fixed price structure, price and natural mortality and variable vulnerability, and the second incorporating both variable vulnerability and price structure which reflect the observed changes in the market place (see above). The objective was to simulate value ($/hour) and size trends over two regions in Spencer Gulf for a simplified comparison of management strategies, in realisation that management is based on a mosaic of spatial units (see Figure 51). For example, the northern grounds are divided into a number of rectangular areas (eg. 15), or other area combinations, based on prawn size and quantity obtained from survey information, see Figure 51. Input from surveys undertaken in February, April, May, June and October, are used to simulate and predict optimal harvest periods for each area or sets of areas based on maximising return ($/hr trawled).

For surveys undertaken in April, the fleet is awaiting results and management decisions as to how, where and when fishing will take place in the northern opening. Data on size and abundance obtained in real time from survey vessels are faxed to the stock assessment/manager and data are simulated to predict best fishing strategies. Simulations require data to be entered in DATAFLEX with summary output in FOCUS on spatial size (size frequency, grades) and abundance, downloaded to GENSTAT for harvest simulations. Appendix 10 provides the GENSTAT code for a simple harvest simulation which predicts value ($/hr trawled), prawn size, and relative biomass changes in an unfished region.

It would be impossible to enter data from all survey stations on one night, so a selection of shots is determined prior to the survey relying on past experience and previous sampling (eg. February). The stock assessment/manager coordinates operations from office via fax modem, fax or phone connection to vessels. Fishing can begin 24 hours following discussion by management meeting some 8-10 hours after the survey is completed and results analysed. Harvesting has well defined spatial sequence. For example, AREA 1 (or AREA 1+2) would be first fished for 6-12 days over the dark moon phase of a fishing period. Subsequently, a re-sampling survey would be undertaken to check the first simulation predictions and further regions are opened, pending results (eg. Areas 3+4+15+12+11). In June, a further survey takes place and further harvesting sequences are allowed depending on stock. In addition to providing information on spatial size and abundance, the February, April and June surveys allow feedback on stock and recruitment strength while daily logbook data and monitoring (via fax) track general exploitation trends on a daily basis. Exploitation is controlled by an initial conservative strategy, direct feedback and nightly catches are maintained but with a lag of 1-2 days owing to the intense competition between operators.

Simulations

An outline of a simple framework for harvest model demonstrates the large effect of different parameters on output.

Simulations of biomass, trawl mass (biomass*vulnerability), biovalue and trawl value were undertaken for two Regions in northern Spencer Gulf to show the effects of variable natural mortality and price on trawl mass and trawl value, see Figure 51. The model has a simple deterministic approach and was developed by Carrick (unpublished). For simplicity the model is based on "closed" fishing system and is realistic in view of the spatial harvesting schemes in Spencer Gulf. Obviously, the incorporation of different exploitation levels would be more relevant to a completely open fishery, managed as a global system. For the simple model F is zero and the model determines the optimum period to harvest based on trawl value ($ hr or $ n.mile trawled) using mixed cohorts over different spatial units using real time data. Therefore, the uncertainty of the main input data (size and density) is minimal and strategies are enhanced by re-sampling in real time.

Main input data are:

Size and abundance (from survey sampling), indexed vulnerability obtained from depletion studies, growth parameters from tagging, mortality (M) parameters or ranges obtained from experiments, ex-vessel prices and different price premiums ranging from 30-50%.

Results indicate that seasonal differences in vulnerability have large effect on trawl mass and value with marked decline from July to August then increase resulting in a number of peaks in mass and value. Clearly, natural mortality and catchability have a large effect on model output, see Figure 52.

For Region 1 (larger prawns) in the vicinity of Middlebank the value peaks in May while in Region 2 (smaller prawns) near Yarraville there are 2-3 peaks in trawl mass and trawl value. The simulations are based on fixed or constant mortalities and it is unlikely that M would be as low as 0.07 month from April to June (see above). However, it may not be unreasonable to use a fixed mortality estimate of 0.08 month for the period April to December. The effect of seasonal price premiums and vulnerability has large effect on model prediction and it appears unrealistic to have a fixed price or vulnerability index in model input. For Region 1 the value has maxim at April/May and for a mortality of 0.08 month, the price would need to be at least 50% higher to have equivalent value in November/December, (see Figure 52). The latter appears unrealistic because a large pulse of supply from Region 1 (eg. 400 -500 tonnes) is likely to prevent price increasing beyond a 50% level on local Australian markets. Therefore, the best strategy is to fish Region 1 from April/June depending on spatial mix with product directed towards export.

Another problem is the unpredictable quantity and effect of aquaculture product from foreign and local producers. It is clearly too "risky" to expect a constant low level effect of aquaculture on markets as large impact occurred in December 1994.

For Region 2 with a fixed M value of 0.1 month there would be a marginal gain in profit by fishing in May, however, for M= 0.08 and a 40-50% price premium the peaks are similar and any increase in price above 50% would result in gain by postponing harvesting. A delayed harvest strategy for Region 2 would provide a reproductive gain providing effort on spawners (November/December) is constrained.

10.3 The effect of fishing and delayed spawning on egg production and "trade-off" due to price premiums

Two spawning sequences were generalised using information obtained from field studies. It is pointed out that large annual differences in spawning have been observed in the field. Early spawning may result in increase in a June recruitment pulse to the fishery providing viable egg production is high. Alternatively, a late spawning with high egg production may result in a greater proportion of February recruits to the grounds. A year later, however, more detailed information relating to the temporal spawning patterns, reproductive "viability" and better SRR and RSR are needed for model development and management.

Results have indicated that multiple spawning or double gaussian relationship and different spatial sequences of gaussian egg production pulses need to be incorporated in models. However, key sampling periods would include February and November/December (see above). Another problem of the model is that it does not incorporate a dispersion parameter (ie. due to movement) but most fishery models do not address this problem. In real life, this is addressed by real time monitoring of size and catch. Most importantly, the spatial sequences in Spencer Gulf harvesting reduce problems associated with movement.

The first type of generalised spawning sequence is termed "normal" and is of triangular form with 5, 10, 40, 25 and 12% of the population spawning from October to February. The spawning pattern is not consistent with results obtained from larval and postlarval settlement trends. That is, multiple spawning may occur in larger prawns and this needs to be addressed to enhance the model. The second type termed "delayed" spawning is skewed with 0, 5, 30, 55 and 10% of the population spawning over the same period.

Region 2 was selected for simulation of the effects of 10 different harvesting schemes on egg production. The model is based on simple recursive differencing using GENSTAT output and a spreadsheet. Main inputs to model include:

- Size distribution and abundance -obtained from real time assessments;
- Growth, algometry and fecundity parameters;
- Vulnerability based on seasonal differences derived from logbook depletion studies;
- Monthly (and daily) instantaneous mortality rates (M, F) obtained from field studies;
- Price structure - obtained from processors and fishers;
- Spawning ogives - simplified from field studies;
- Different numbers and periods or sequences of fishing effort (days fished)-generalised from Historical operations with fishing taking place over dark moon.

The model uses a variable M as this appears more realistic (see above) and is validated from field study. The effect of delayed spawning, different fishing strategies, and fishing mortality rates (0.15 and 0.05 day) on egg production were examined.

The hypothetical fishing strategies considered were:

1. Zero fishing with M=0.1 month (April-June); M=0.07 month (July-November); M=0.1, (November- February).

2. A 10 day fishing pulse in May with F=0.15, 0.08 day, M=0.033 day. M=0.07 month, (June-November); M= 0.1 month (November -February).

3. A 10 day fishing pulse (November-December) with M=0.1 month (April- mid June); M = 0.07 month (June - November) and F = 0.15, 0.08 day(10 days, mid November); M = 0.1 (December - February).

4. Two fishing pulses of 5 days in each November-December and December-January with same M rates as 2 (above).

5. One 10 day pulse of fishing from mid December with same rates as 2(above).

6. One 10 day pulse of fishing from mid October with same mortality rates as 2(above).

7. Three pulses of fishing with 2 days from mid October and 3 days from mid November and 5 days from mid December.

8. Two pulses of fishing with 3 days from mid November and 7 days from mid December.

9. Two pulses of fishing with 3 days from mid October, F=0 November(Closed) and 7 days fishing mid December.

10. Two pulse of fishing with 5 days from mid-October, F=0 November (Closed) and 5 days fishing mid December.

Simulation results are illustrated in Figures 53 and 54. For normal spawning and high F values strategy 5(S5) produced 83.4 million eggs per nm while strategy 8 and 4 produced 67.7 and 62.8 million eggs, respectively. Fishing in May resulted in substantial reduction in egg production with a value of 25.5. Similarly, a 10 day fishing pulse in mid October (S6) resulted in low egg production. Therefore, strategies to delay fishing in order to increase egg production are best achieved by postponing fishing until mid November or having an initial small pulse (initially 3 days) followed by zero fishing in November and a larger pulse (7 days) from mid December.

Lower Fishing mortality rates resulted in substantially larger egg production for average spawning. Similarly, reproductive gains were reduced by early exploitation (eg. S2 and S6). All strategies except 2 and 6 resulted in egg production exceeding 67% of the maximum level (i.e. zero fishing).

Delayed spawning results in substantially less eggs produced at high F values than normal spawning. The "intuitive" objective has been to allow about 50% of the main northern population to spawn in the late spring -early summer season by delaying fishing on dense subpopulations which are delineated by survey sampling and using closures as depletion buffers.

The main points are:

- Premature fishing at Region 2 (10 days in both May and October) would result in substantial reproductive loss for lower or marginal economic gain compared to fishing in November/December. Furthermore, there is a greater proportion of soft-shell prawn in October due to partial synchrony in moulting which would lower the price structure.
- Phasing in fishing with initially low exploitation levels (S4 and S5) from mid November results in optimal economic return and would minimise risk of reproductive depletion.
- A delay in spawning results in substantially lower egg production at high exploitation levels and only strategy 5 (largest delay) approaches optimal level.
- Larval studies and modelling currents suggest that greater wastage of eggs through unfavourable advection could occur if spawning is delayed. Premature harvesting at high exploitation rates coupled with a delay in spawning would increase the risk of stock decline.
- A high recruitment to grounds (eg. February) may not result in large egg production because the recruits may not be reproductively "viable" for a long time (eg. February recruits, 10-12 months later) and the population may be largely fished down before effective spawning if there were no management constraints on exploitation (see above).
- Exploitation levels on pre-spawners (November-February) needs to be controlled for stock maintenance. Nominal effort should not approach those levels of 1985 and 1986 (37.4-36 thousand hours) where recruitment is low.

The studies of fishing power are incomplete, but not trivial, and there is a strong need to obtain better estimates of the effective effort trends, especially on pre-spawners. Fishing power in 1986 was shown to be significantly higher than 1987-1989 which is mainly attributable to skipper kill. Assuming a minimum 12% decrease in fishing power from 1987 to 1989, this would indicate that the effective effort exerted in 1986 would be equivalent to 40,407 hours (cf. 36,078 nominal hours) compared to 28,029 hours exerted in 1989.

Further work on development of harvest models is planned in collaboration with process modellers and GIS experts, which will enable a greater understanding of the effect of fishing on different spatial units and lead to enhanced market models and stock assessment procedures.

The problem of calibrations of effective effort remains unclear and is currently being addressed by the author in conjunction with industry. For a number of reasons, the cpue index may provide a misleading estimator of stock abundance over time. The effects of environment and fishing on SRR and RSR need to be estimated before "reliable"estimates of effective effort can be determine with the purpose of establishing some optimum equilibrium catch effort levels.

11. CONCLUSIONS AND RECOMMENDATIONS

The harvest strategies adopted in Spencer Gulf by the author in collaboration with industry since 1981 have been adaptive, utilised trial-and-error and improved over time with increase in understanding of the spatial dynamics through trawl sampling, mark recapture studies and analysis of logbook data (eg. depletion and size composition of catch). The FRDC study has enabled the applied and fundamental aspects to be directly "connected" for use in management. The management has a strong link to the population and fishery biology. It must be realised that Industry has a major role in the management and research of the Spencer Gulf prawn fishery. The study has addressed the key factors effecting recruitment in the Spencer Gulf and a general comparison made with an Oceanic fishery (West Coast). It is apparent that each fishery is different but similar, on one count, that spatial structure , spawning sequences and dispersal are important factors structuring recruitment. A significant relationship between recruits, spawners and weather has been determined in Spencer Gulf.

In light of findings, the research can now be directed (or focused) towards more comprehensive process and econometric modelling and spatial systems and linked to field studies. Most importantly, spatial systems and GIS will enable complex analyses and data to be clearly communicated to the Spencer Gulf and West Coast Management Committee and fishers. There will always be a need to refine and test parameters and models. Clearly, numerous factors influence recruitment patterns to Penaeid fisheries and recently the importance of spawners has been verified in three Australian prawn fisheries.

In Spencer Gulf there is a balance in management objectives relating to maintenance of egg production and economic imperatives which means that price structure, value of catch and costs of fishing have relevance to development of harvest models. Fisheries should never be allowed to be managed solely by biologists, fishermen or economists. It is pleasing to note that in Spencer Gulf most fishers support this conclusion. The management requires a range of skills including those of the fishers and processors.

In 1986/87 the SPG fishery declined due to the combined effects of over fishing and weather. Subsequently, action was taken and the fishery recovered and has remained fairly stable. Industry must realise the need to be "conservative" and objective and adapt harvesting schemes and management policies which have longer term economic benefits.

In review, it is clear that industry has gained substantial longterm financial benefits from the research over the last 12 years owing to improvement in prawn size and value, maintenance of stock and decreased costs of fishing due to less days, and efficiencies attributable to locating and directing the fleet to regions and periods of higher value ($/hr trawled). Overall, harvest strategies developed have resulted in positive economic outcomes due to reduction in the costs of fishing and stable to increasing economic returns over longterm.

The management of Spencer Gulf has been driven by applied fishery research and basic economics. The management and research has been innovative.

Some of the innovative management tools developed in Spencer Gulf include:

- moon closures (from 1981);
- reproductive spatial closures and delays in exploitation on assumption of a SRR on simple depletion models (1981);
- area closures based on real time sampling (1980);
- spatial harvest schemes and schedules (1981);
- real time management schemes for change (1984);
- closure index schemes for easy and rapid change to closure lines (1984);

- survey sampling using 10-14 vessels with trained crew (1981);
- adaptation of statistical methods for spatial trends, evaluation of closures, assessment of the effects of fishing and for stock assessment (1980);
- re-sampling ("spot surveys") for refinement of harvesting schemes and reducing uncertainty (1983);
- experimental field manipulation of fleet for estimation of parameters and separation of confounding effects of fishing and catchability (1981);
- commercial measuring of size at sea by trained fishers for spatial assessments (1980);
- use of tagging as a management tool and design of tags and efficient methods (1981);
- development of real time harvest models (1987);
- "Mid night" openings and methods to enhance quality of catch (1994);
- methods for understanding and assessment of the fishing power of the fleet (1987);
- rotation of grounds (1990).

The FRDC research has enabled valuable life history information to be obtained which has fundamental and applied value. Most importantly, the FRDC program has laid the foundation for juvenile studies and a most important process driving the fishery, reproductive viability and egg production.

It is recommended that research maintain the close link with industry and obtain even greater support and cooperation. It must be realised that research is expensive and there will always be a need to focus on fundamental research problems. Funding for a comprehensive study addressing priority research objectives cannot be derived solely from fishers via license fees on a "user pay " system.

The work has demonstrated that reliable estimates of mortalities and the effects of fishing can be obtained from simple statistical modelling providing that there is manipulation to separate confounding effects. The recent development of AD Model Builder and its auxiliary linked system AUTODIFF by David Fournier (Otter Software, Canada) provides scope in this area as does adaptation of some model based systems using S-Plus (Stephen Smith, personal communication). Recent development of GENSTAT5 and S-PLUS allow potential for high level statistical and GIS model development which can now run on Pentium PC machines.

A major problem, as always, is obtaining funding to provide technical support (manpower) but also, access to high level expertise (statistical modellers, process modellers, GIS systems analysts, data base systems analysts and programmers). It is unlikely that a broad range of skills would be assembled within South Australia and a solution to the problem is to seek collaboration with overseas agencies and Universities and the CSIRO. An important discipline needed in prawn fisheries relates to econometrics and collaboration with The University of Sydney (Dept. Ag. & Resource Economics) provides a means of obtaining this type of expertise and collaboration.

RECOMMENDATIONS FOR FUTURE RESEARCH IN SPENCER GULF

1. Analyse, report and publish results of FRDC and related work.

2. Extend and develop collaborative links with foreign and Australian researchers.

3. Enhance and maintain cooperation and collaboration with fishers and the processing sector.

4. Determine trends in fishing power and effective effort trends, in conjunction with industry.

5. Prioritise research focus and direction. The FRDC program has enabled information to be obtained to allow an overall appraisal of both applied and fundamental research objectives. The following areas of research are considered to have main priority:

   (a) Reproductive "viability" of different spatial units of the stock.
   This is required for SRR, RSR and effort, harvest models and for development of harvesting schedules. The program requires:

   - determination of insemination frequency at size over different areas;

   - develop a GIS system for real time assessment of regional reproductive viability based on survey sampling;

   - size fecundity relationships over main areas and test of different effects associated with numbers or biomass of spawners. Does fecundity vary with numbers or biomass of spawners ?

   - determine temporal and spatial patterns in spawning. This requires histological sectioning of samples (see above);

   - development of a tool or a methodology for direct field assessment of reproductive status and level of spawning;

   (b) Spawner recruit, Recruit Spawner and "Equilibrium yield" relationships in the fishery.

   - develop appropriate spatial models incorporating larger data;

   - enhance and maintain environmental data base with set-up of a logger for continuous monitoring over longterm of water temperature, wind and sea level. Collaborate with the National Tidal Facility (NTF) and The Department of Meteorology (Adelaide);

   - maintain survey assessment techniques (i.e. ongoing) for time series studies of SRR and RSR and effects of effort. It was suggested that a minimum of 18-27 years of data are required for realistic time series analysis;

   - enhance and maintain industry support (by incentives) for collection of size frequency data of catch and logbook information and grade data to allow further assessment of SRR and RSR for spatial and global scale. Use information obtained from this and survey assessments to develop models for equilibrium yield and effects of effort on recruitment and catch over longterm.

(c) *Enhance harvest models*

- collaborate with process modellers and econometricians;
- incorporate dispersion parameters and dgaussian spawning trends;
- test for density effects on growth using tagging/survey assessment
- determine mortality of 1+ to 2+ Year cohorts from December to February to April using manipulation, survey assessment and tagging.
- incorporate Spatial GIS and SRR in models;
- incorporate costs of fishing in models (fixed and variable).
- determine risk and biological reference points.

(d) *Experimental effects of change to spatial spawners- on recruitment and subsequent catch.*

- manipulation requiring industry support to change spawners- steps of high to low and adapt intervention time series analysis;
- monitor levels of viable spawners and recruits by trawl survey;
- monitor levels of settlers and juveniles in nurseries (see below);
- address to questions:
- does the level of spawners effect settlement pattern?
- does large settlement result in large juvenile populations?
- does level of settlement effect recruitment to grounds?
- what are the major factors influencing survival in nurseries ?

(e) *Develop a longterm program for monitoring settlement to nurseries and factors effecting juvenile nursery populations?*

- optimise and reduce settlement and juvenile sampling program;
- estimate annual survival patterns in nurseries and relate to recruitment;
- determine effects (and trends) of weather and initial density on survival;
- experimental determine effects of crowding on survival and growth;
- determine effects of blue green algae on settlement and survival over longterm at strategic "effect" sites and controls.
- determine effect of blue green algae on survival and growth using laboratory manipulation.
- determine effects of temperature regimes and desiccation on survival and growth by laboratory experimentation and relate to field studies.

(e) *Maintain studies on fishing power, effort standardisation and depletion. Ensure date reliability.*

(f) *Integrate GIS systems for stock assessment and real time development of harvest strategies and models.*

- clearly communicate to industry via visual representation;
- develop a white board system for efficient real time management and transfer of information to industry.

(g) *Maintain settlement and juvenile monitoring and habitat studies at "environmentally sensitive" sites and main nurseries.*

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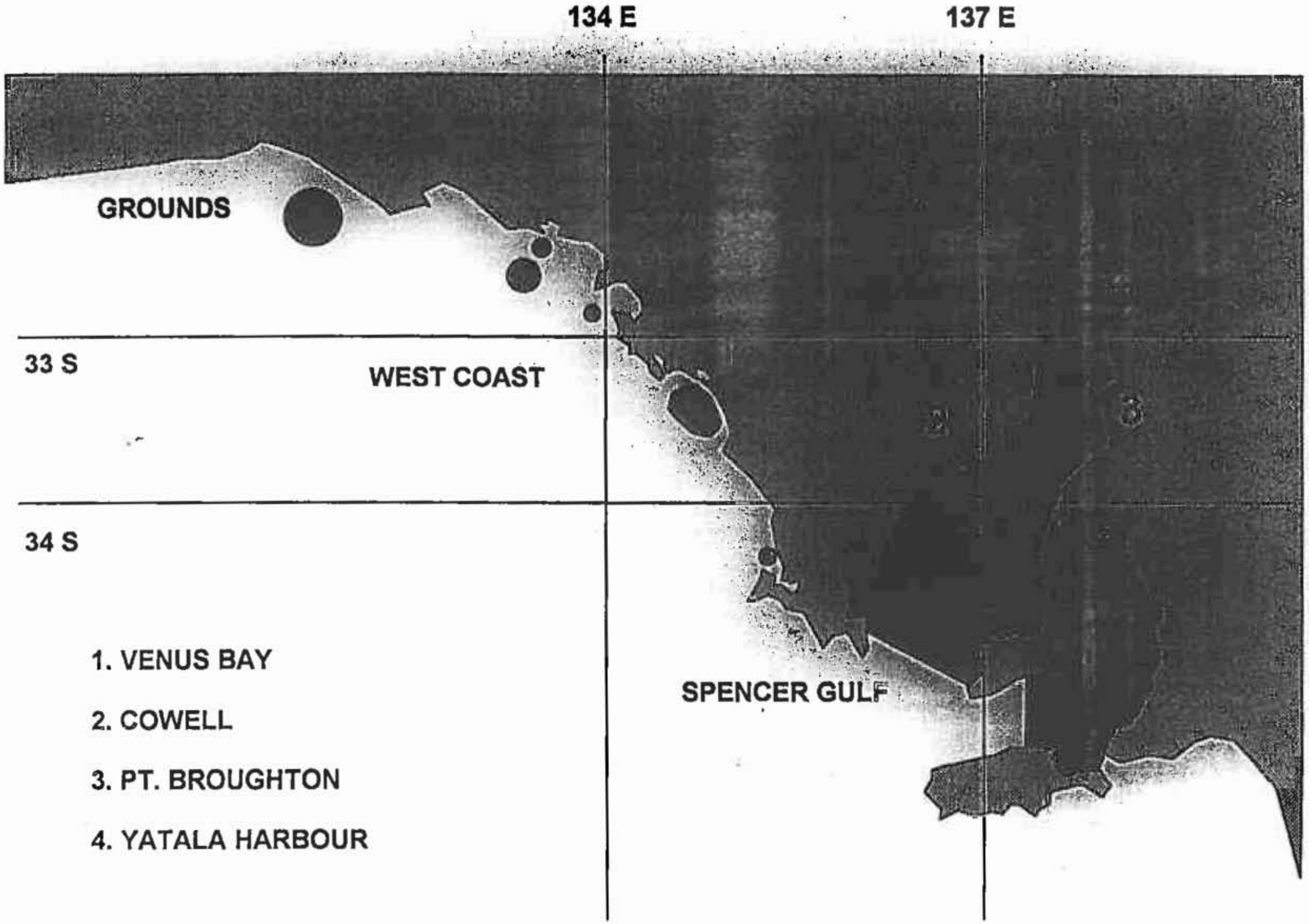
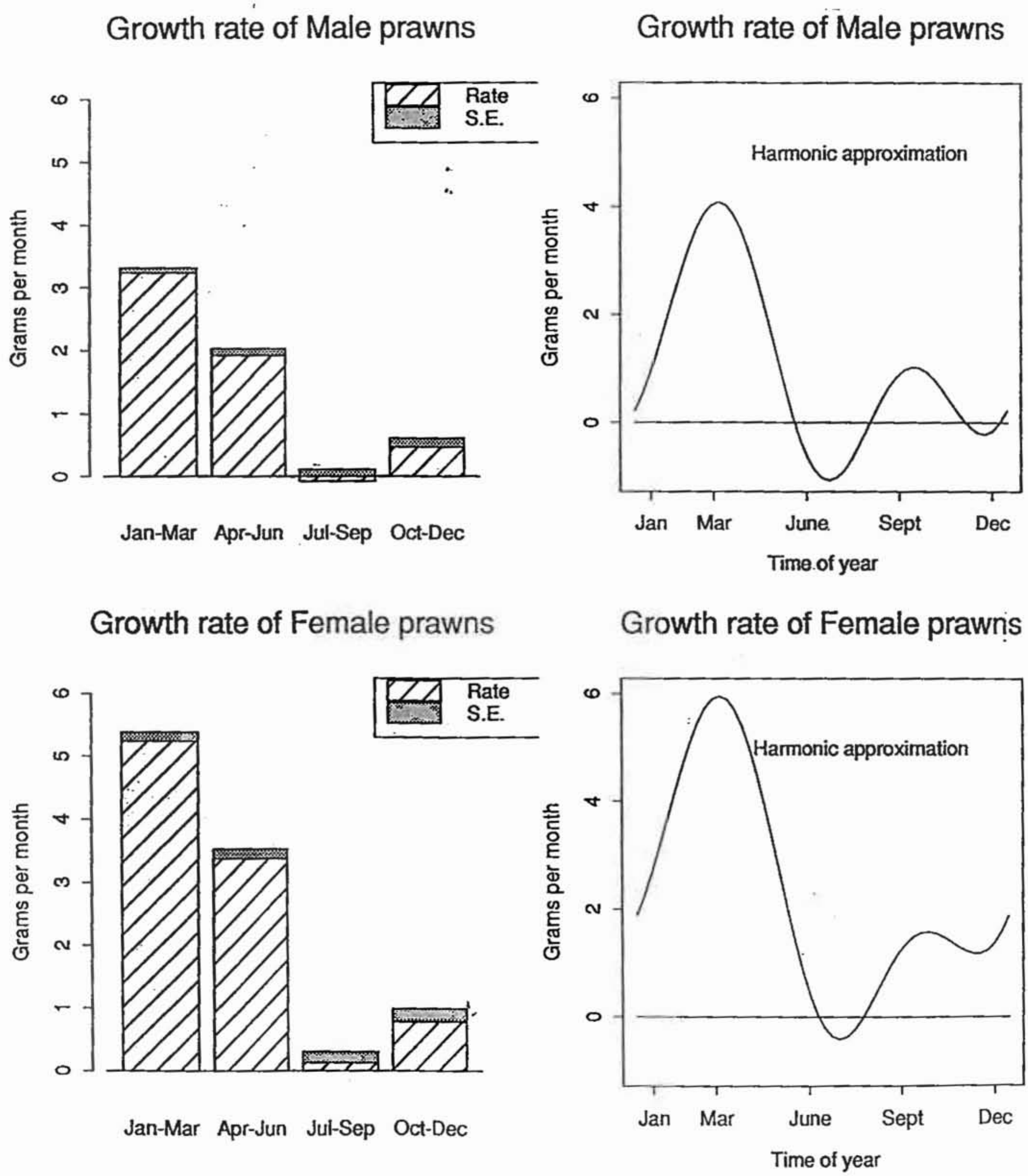


Figure 1: South Australian prawn fisheries.



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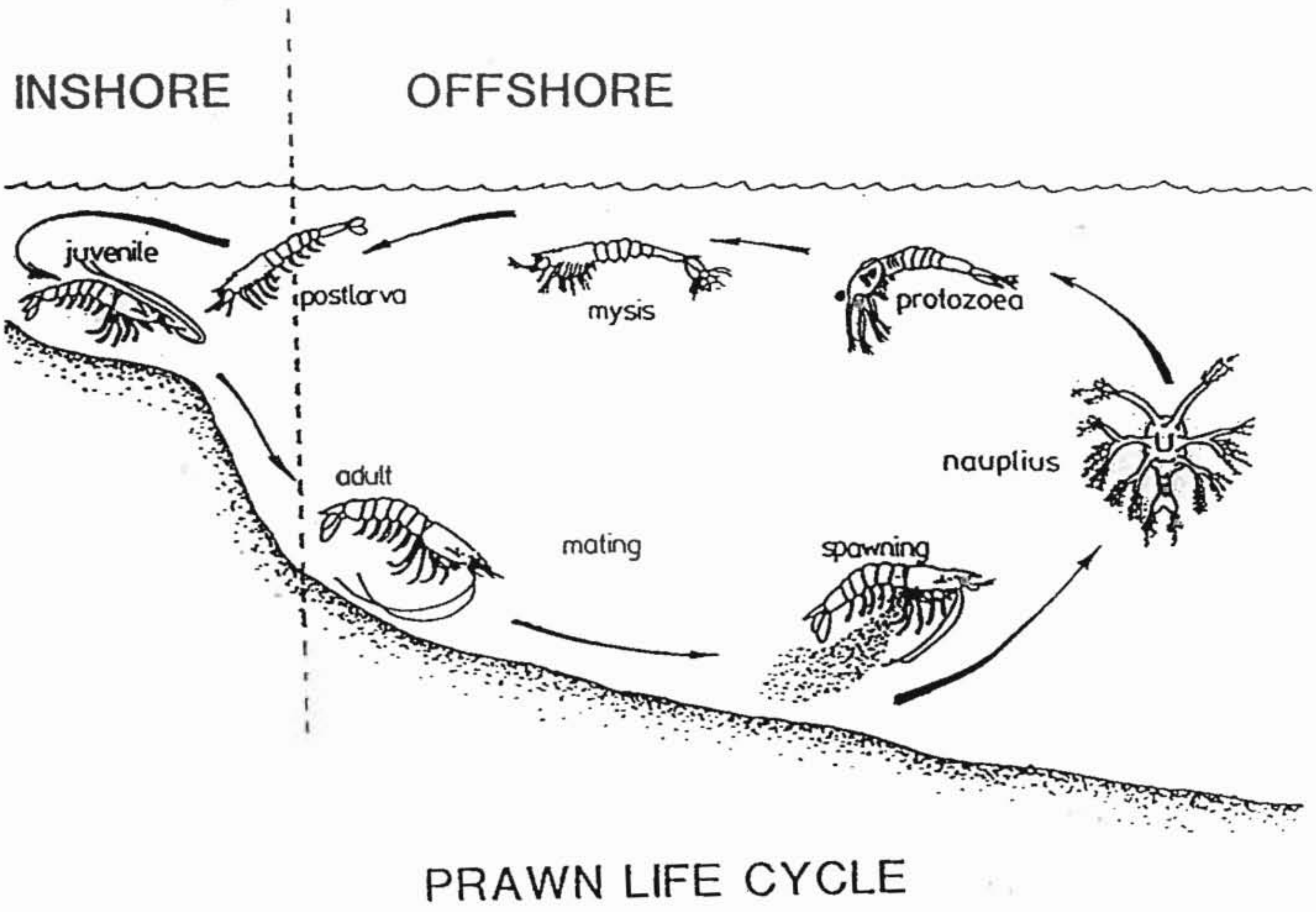

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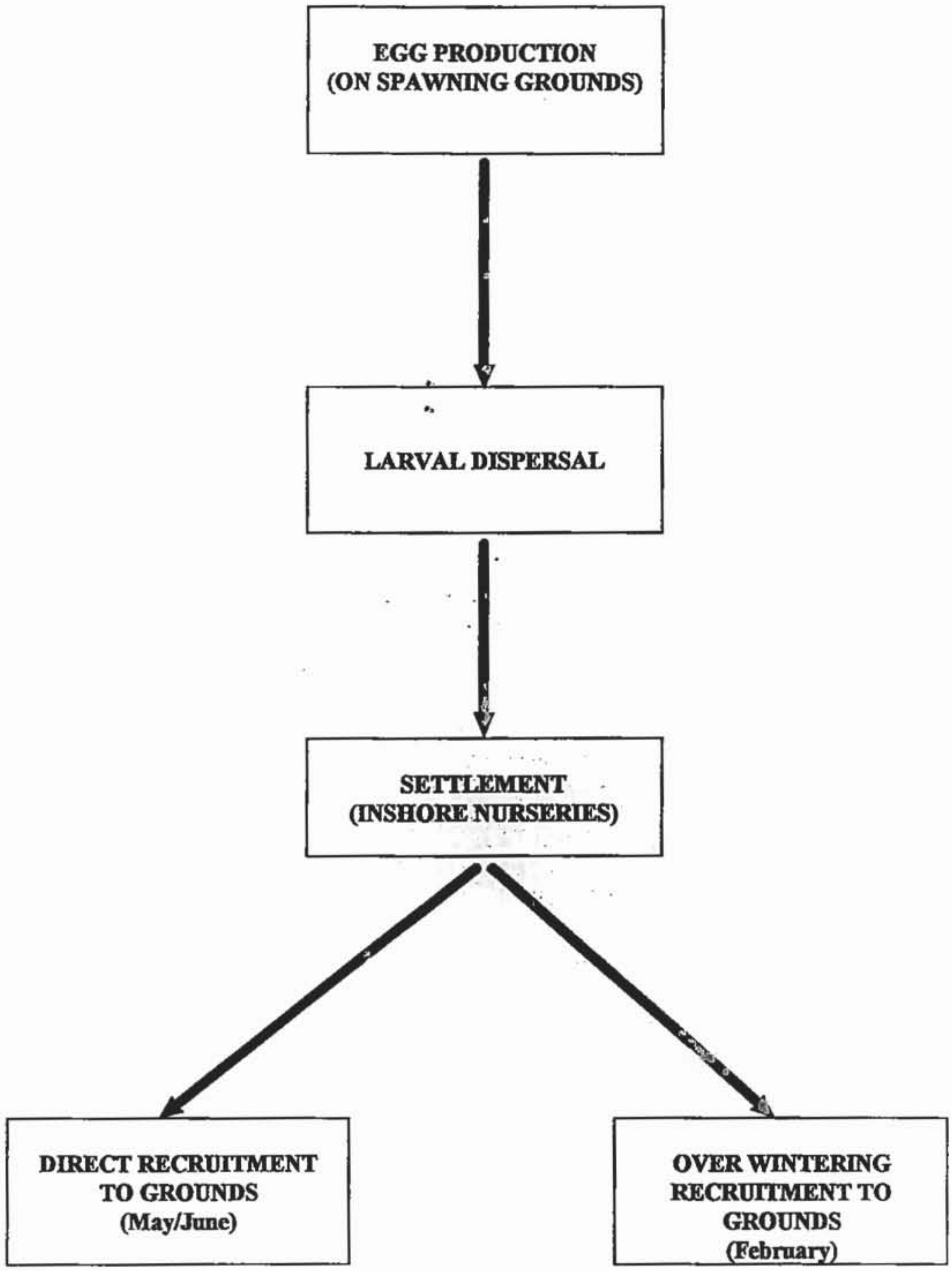

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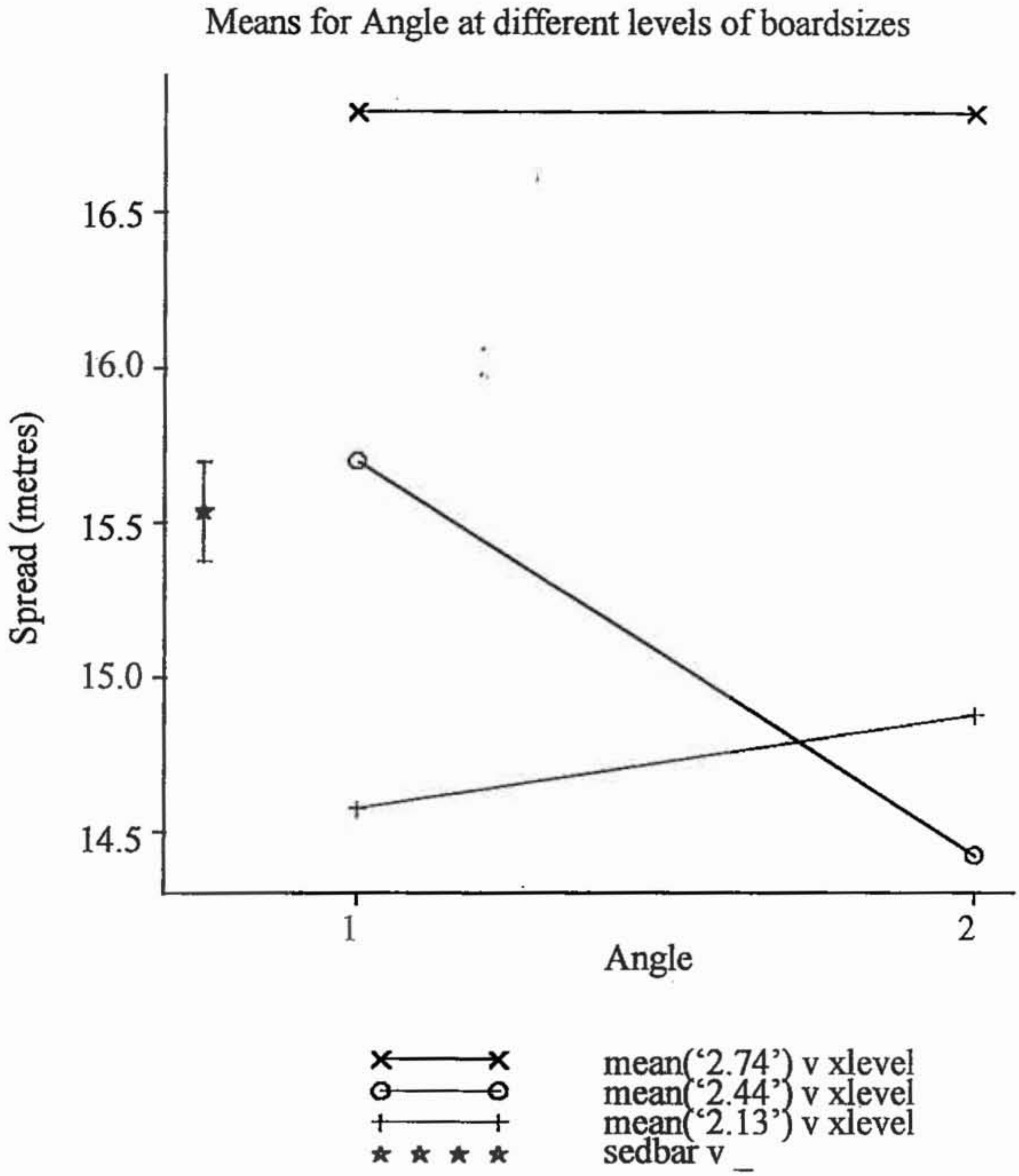

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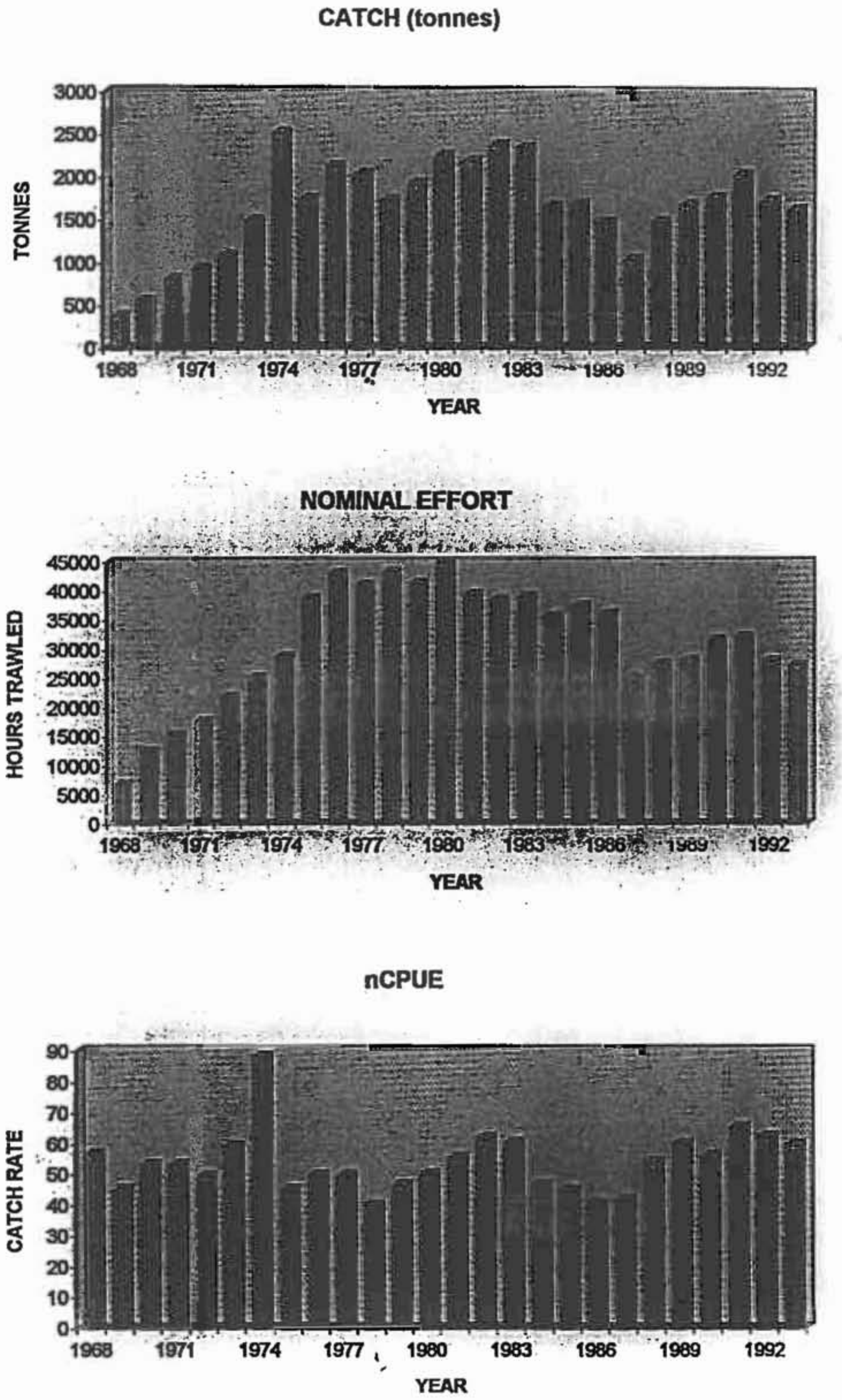

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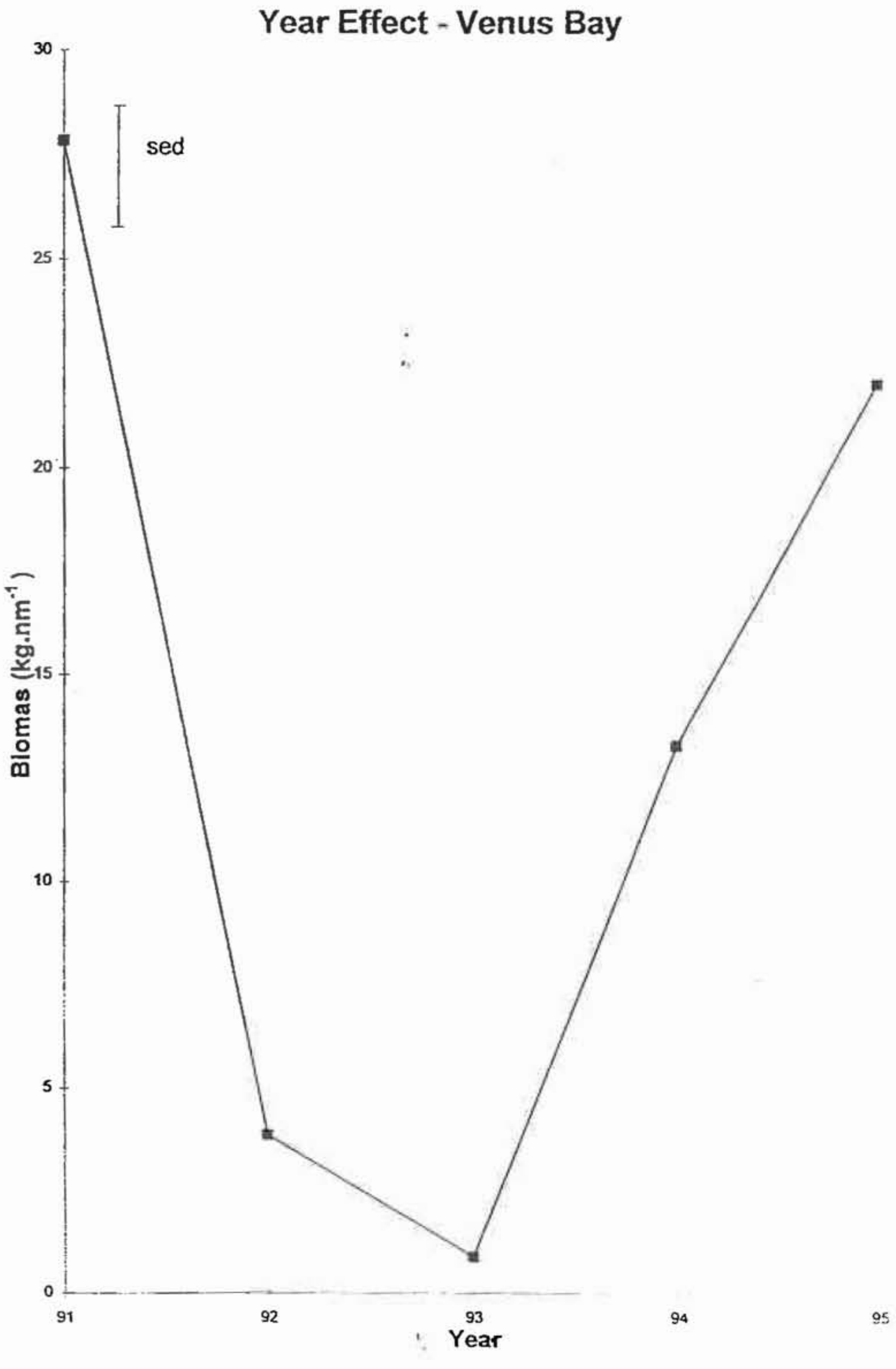

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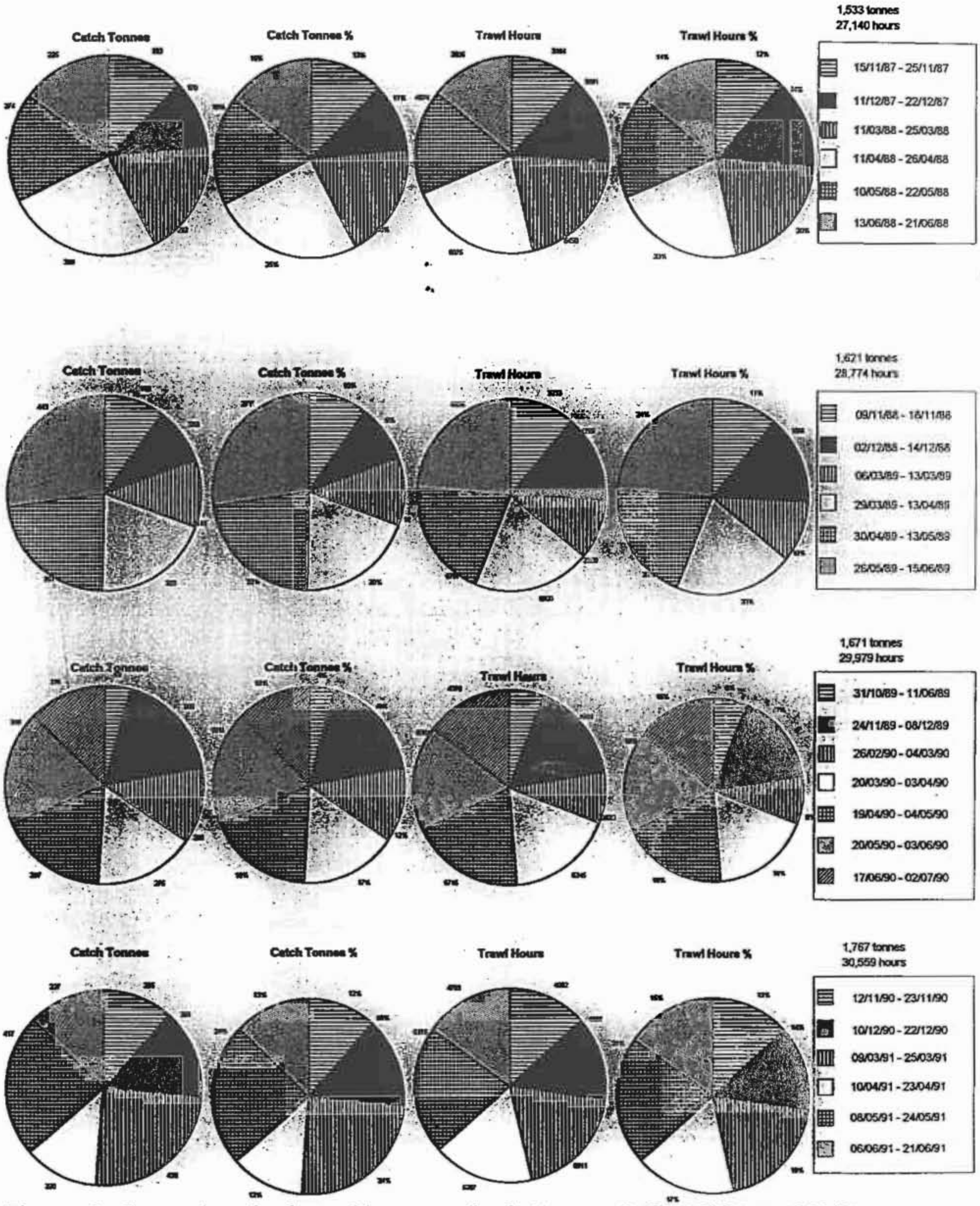

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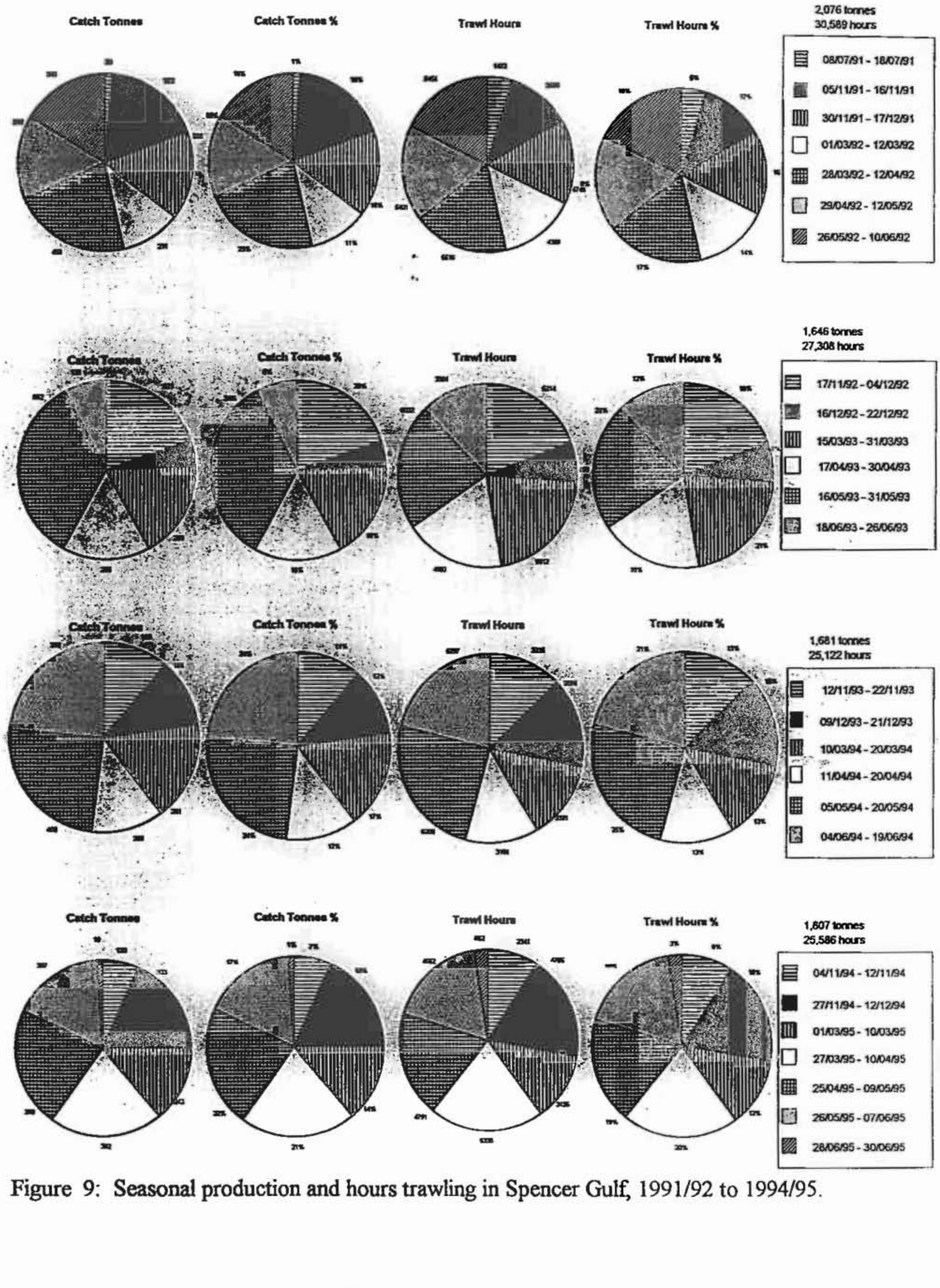


Figure 9: Seasonal production and hours trawling in Spencer Gulf, 1991/92 to 1994/95.

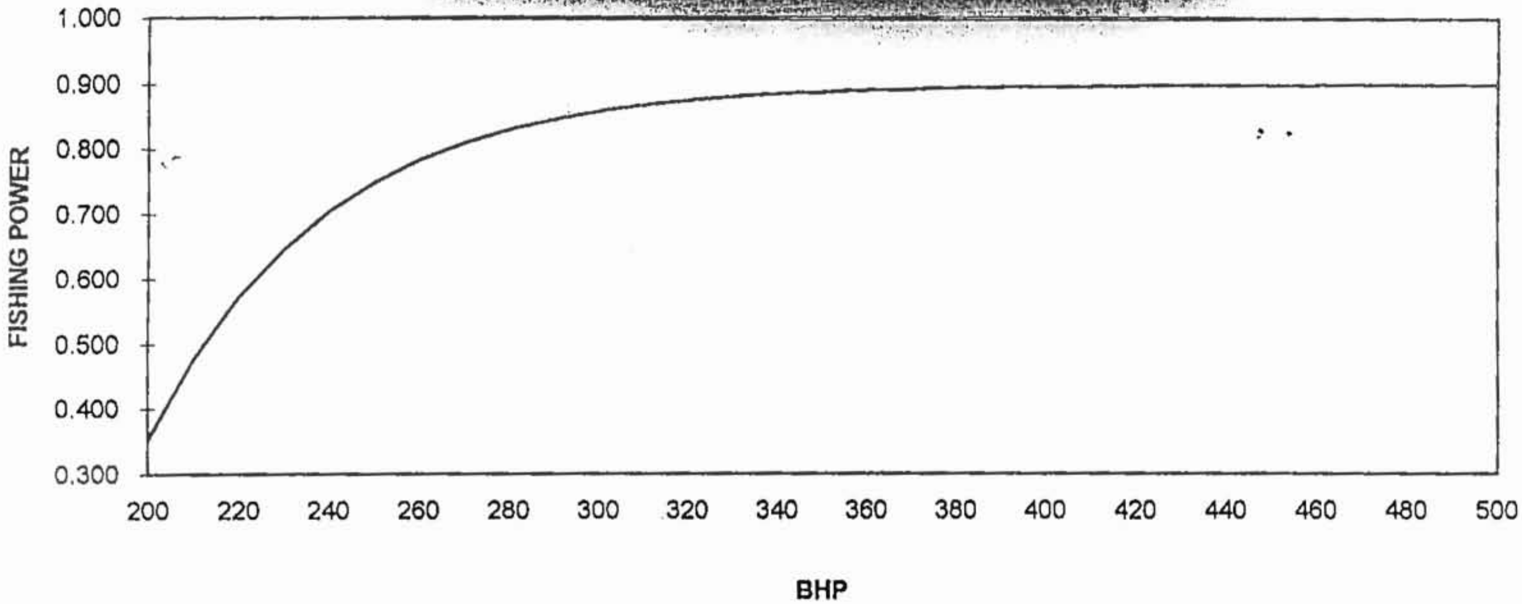


Figure 10: The relationship between engine bhp, vessel mass, length and fishing power in Spencer Gulf.

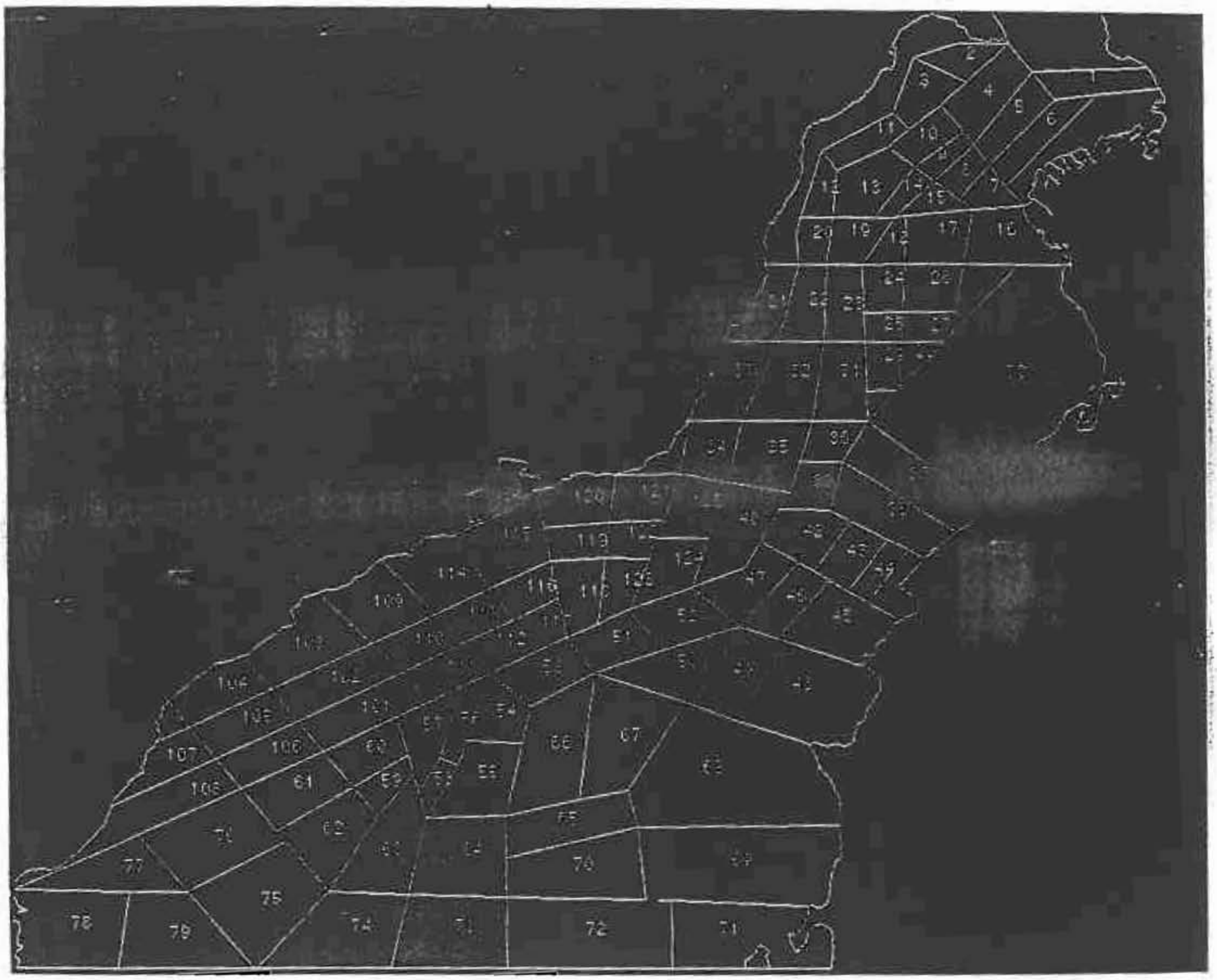


Figure 11: Logbook fishing blocks in Spencer Gulf.

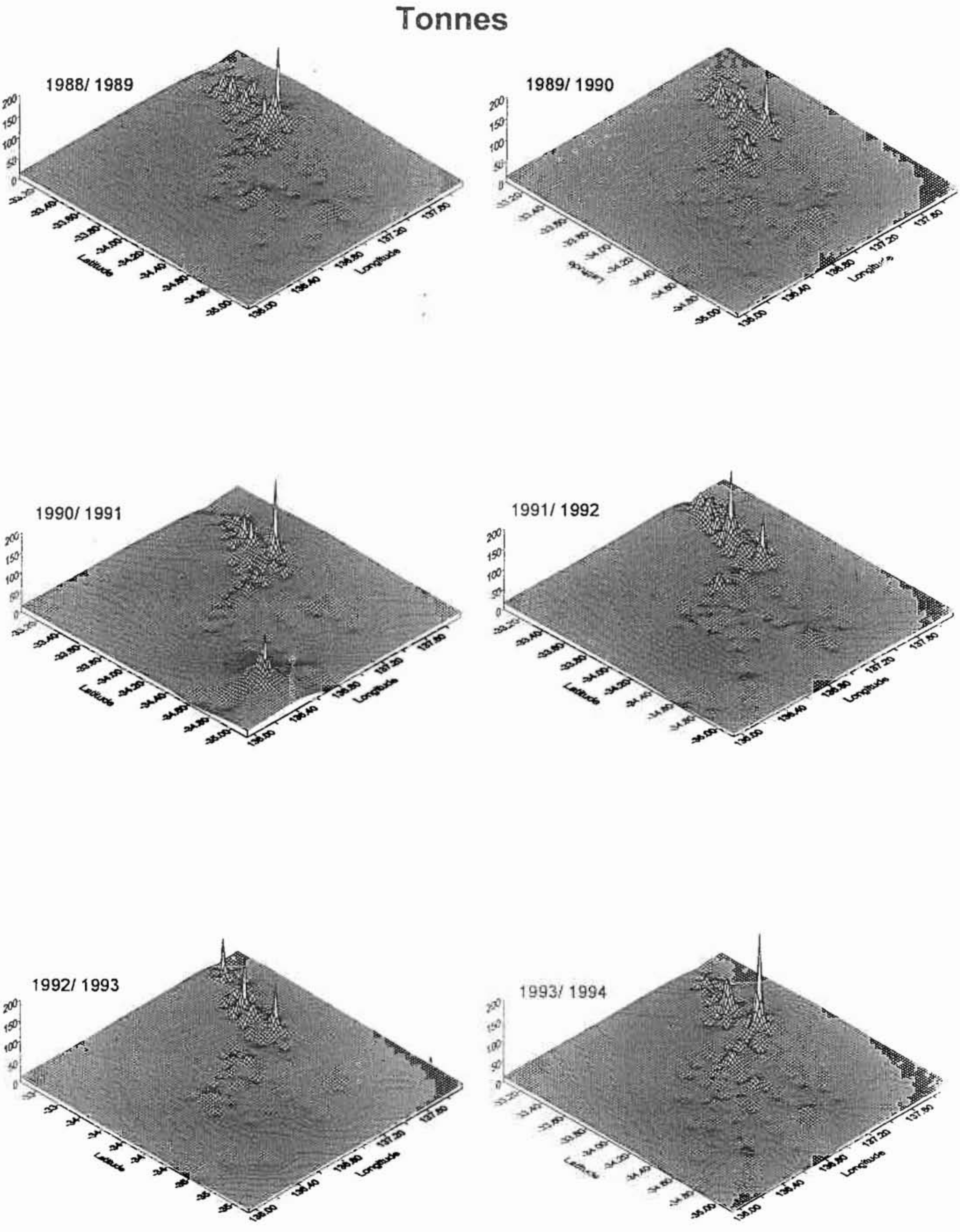


Figure 12: The spatial distribution of prawn P.latisulcatus catch in Spencer Gulf, 1988/89 to 1993/94

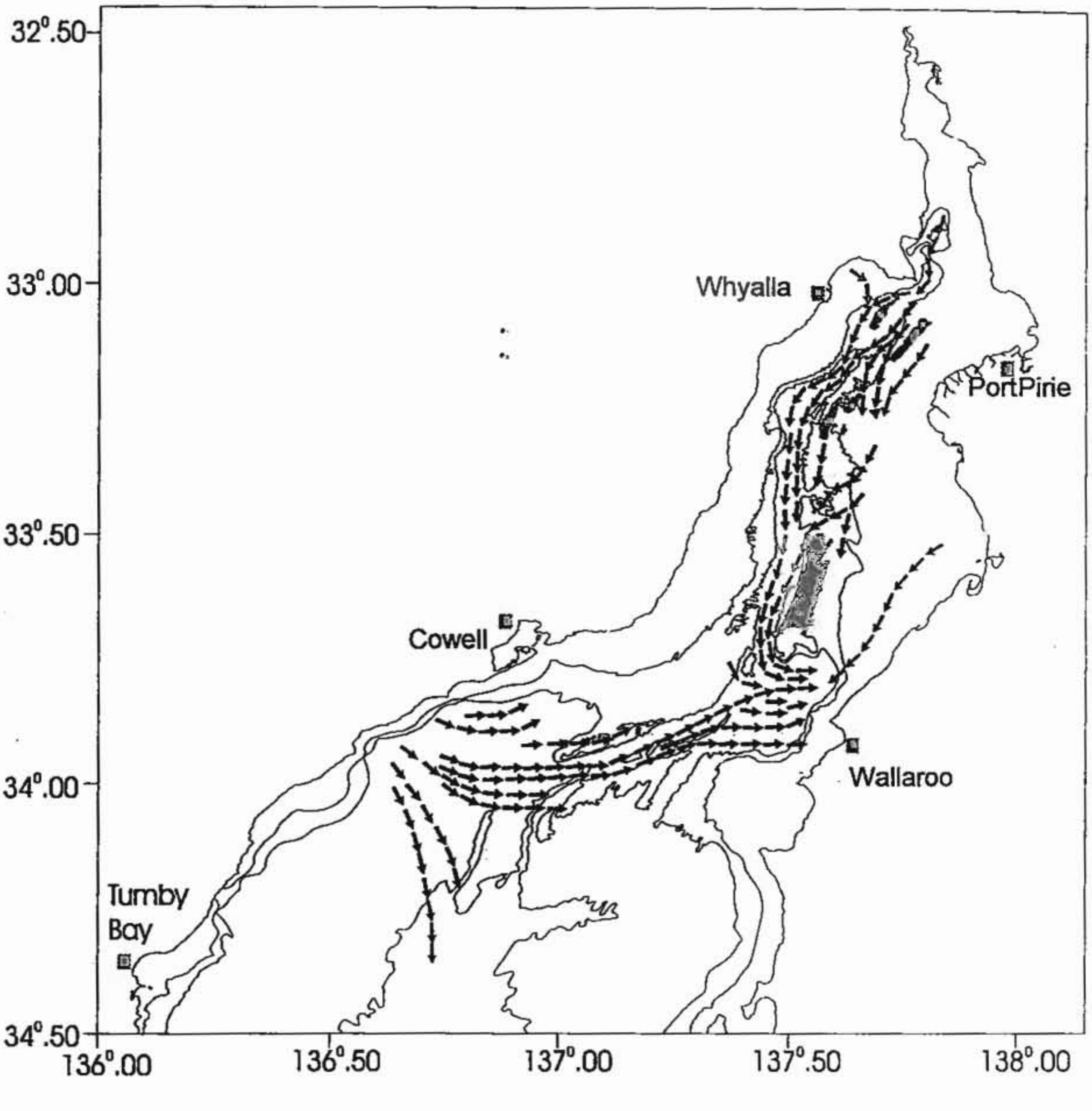


Figure 13: A general model of adult P. latisulcatus movement in Spencer Gulf based on mark - recapture studies

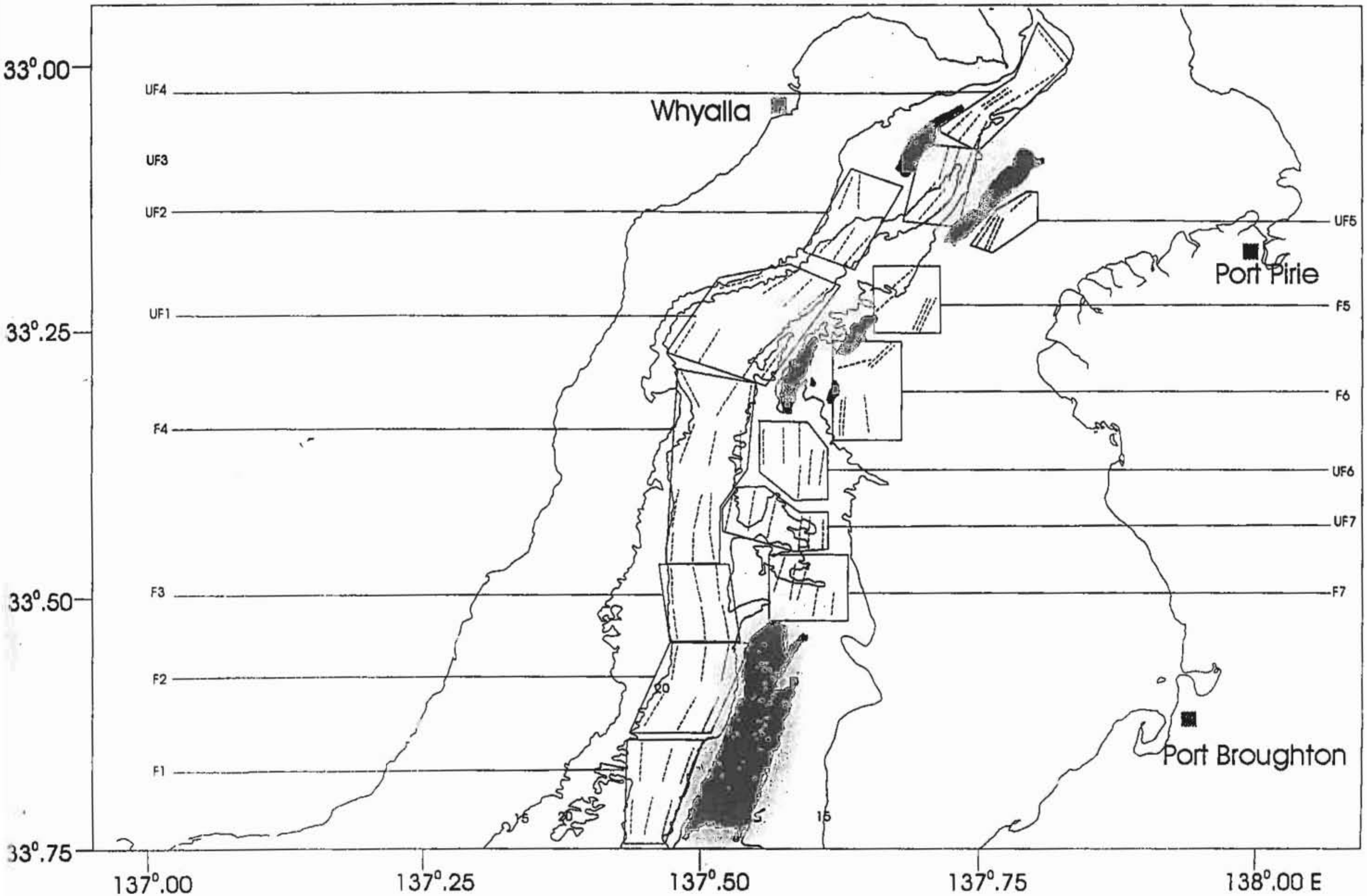


Figure 14: Layout of fleet manipulation to separate and estimate fishing and natural mortality of P.latisulcatus in Spencer Gulf UF1 to UF7 represent unfished regions while F1 to F7 represent fished regions.

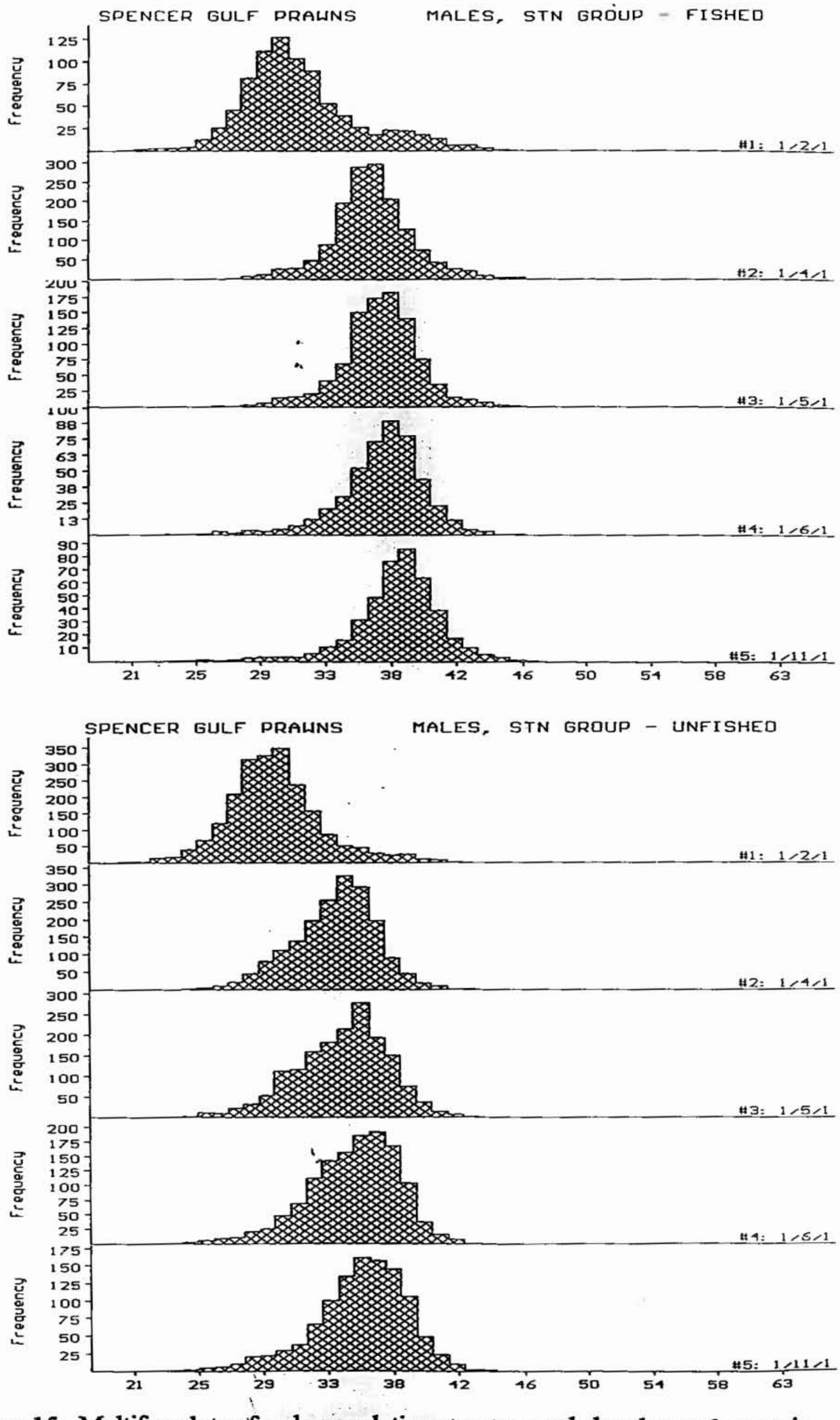


Figure 15: Multifan plots of male population structure and abundance changes in fished versus unfished station groups from Februar[illegible]

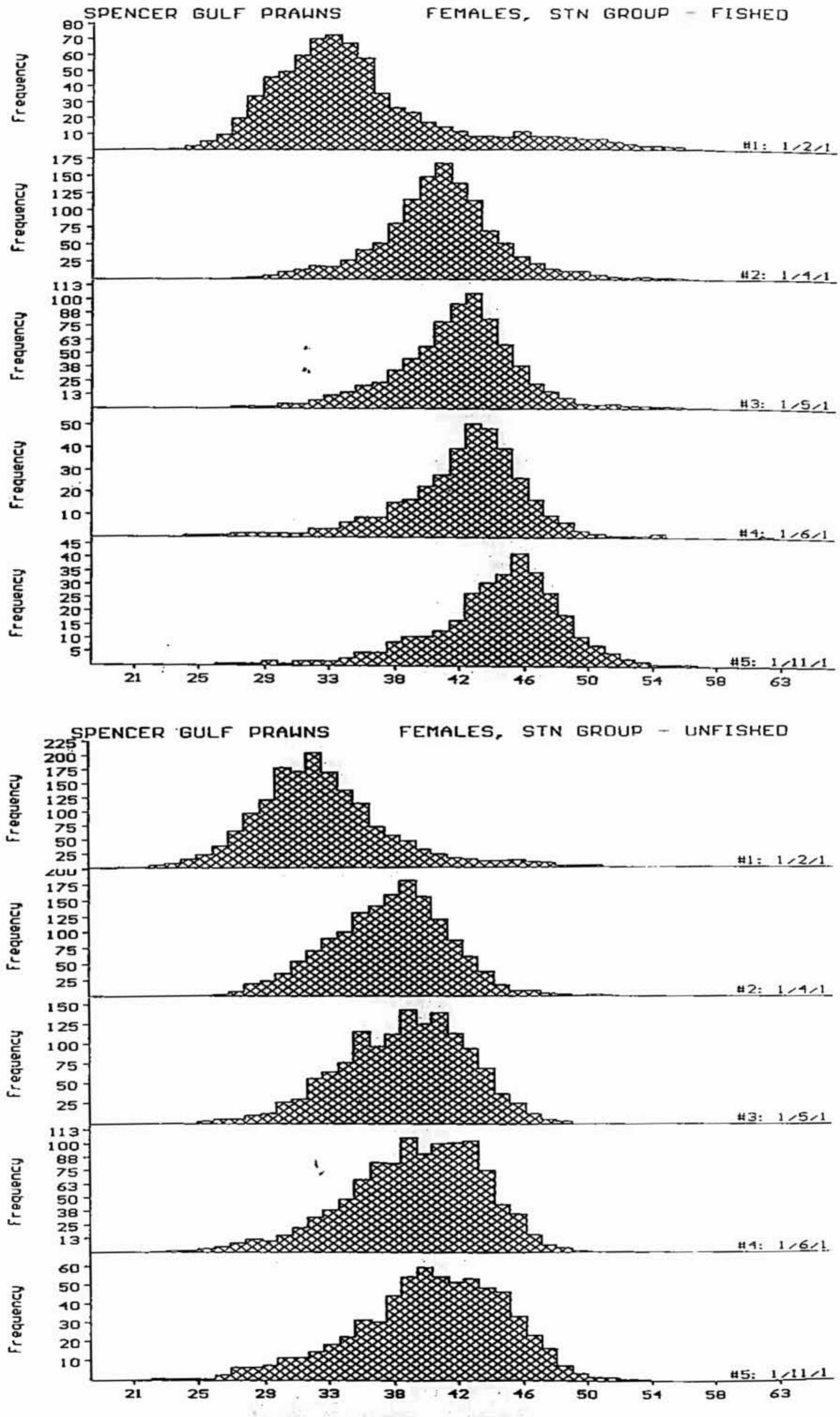


Figure 16: Multifan plots of female population structure and abundance changes in fished versus unfished station groups from February - November 1988

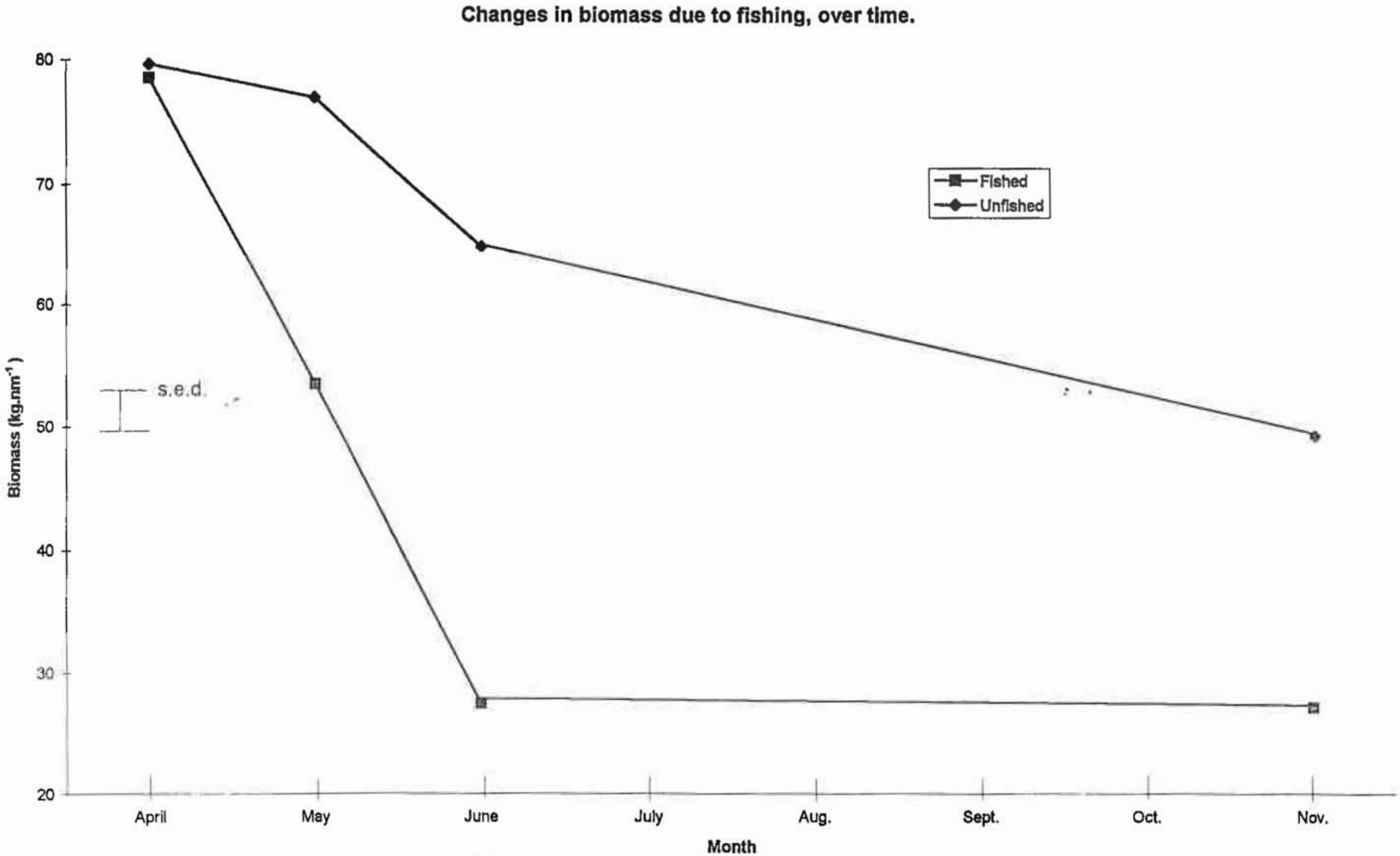


Figure 17a: Comparison of biomass in fished versus unfished regions in Spencer Gulf, April to November 1988. Based on trawl assessment with fishing beginning after sampling in April and a total closure of the Gulf from June to November 1988.

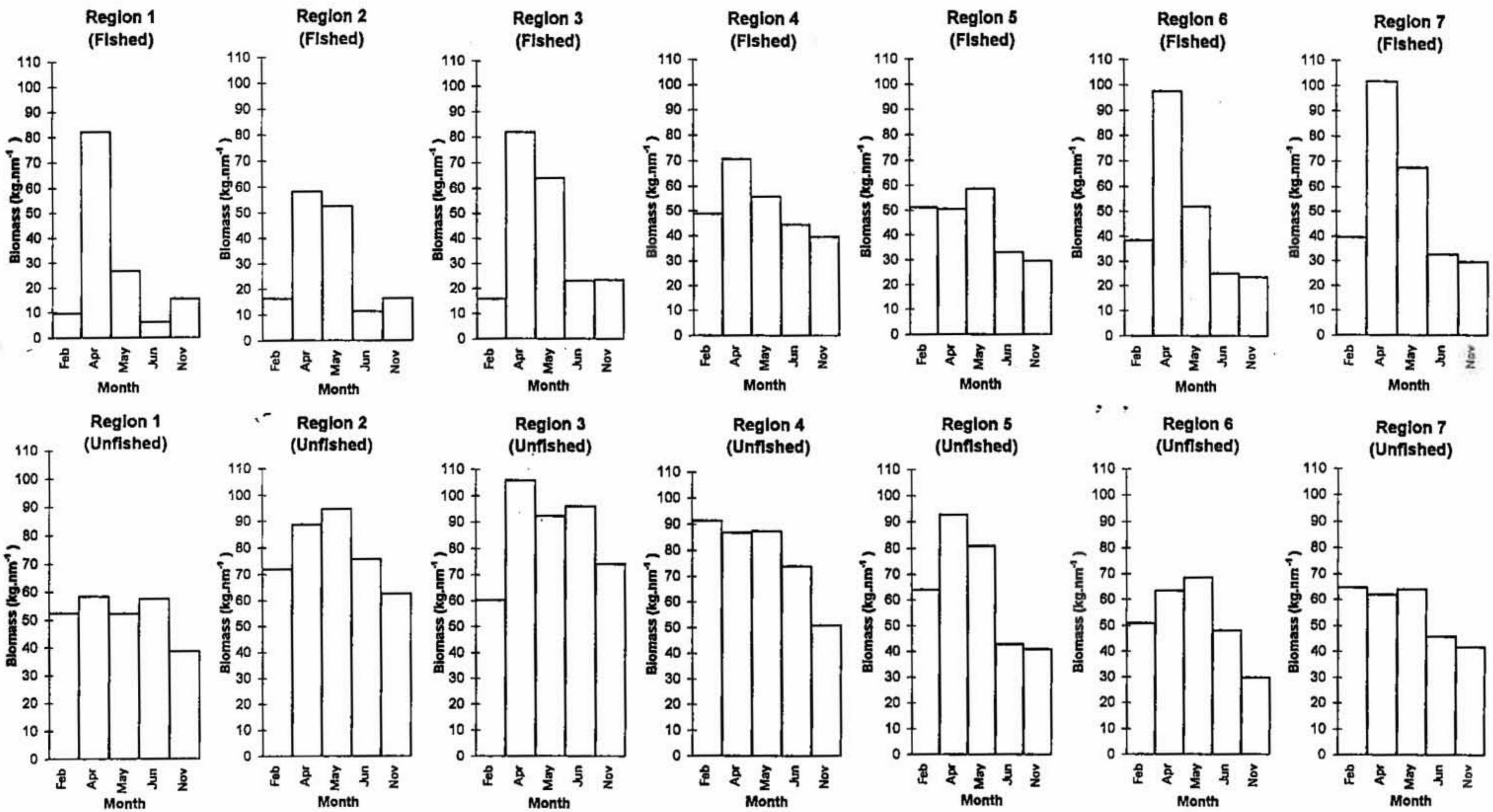


Figure 17b: Mean biomass (kg.nm^{-1}) changes from February to November 1988 in fished and unfished regions over different levels of fishing.

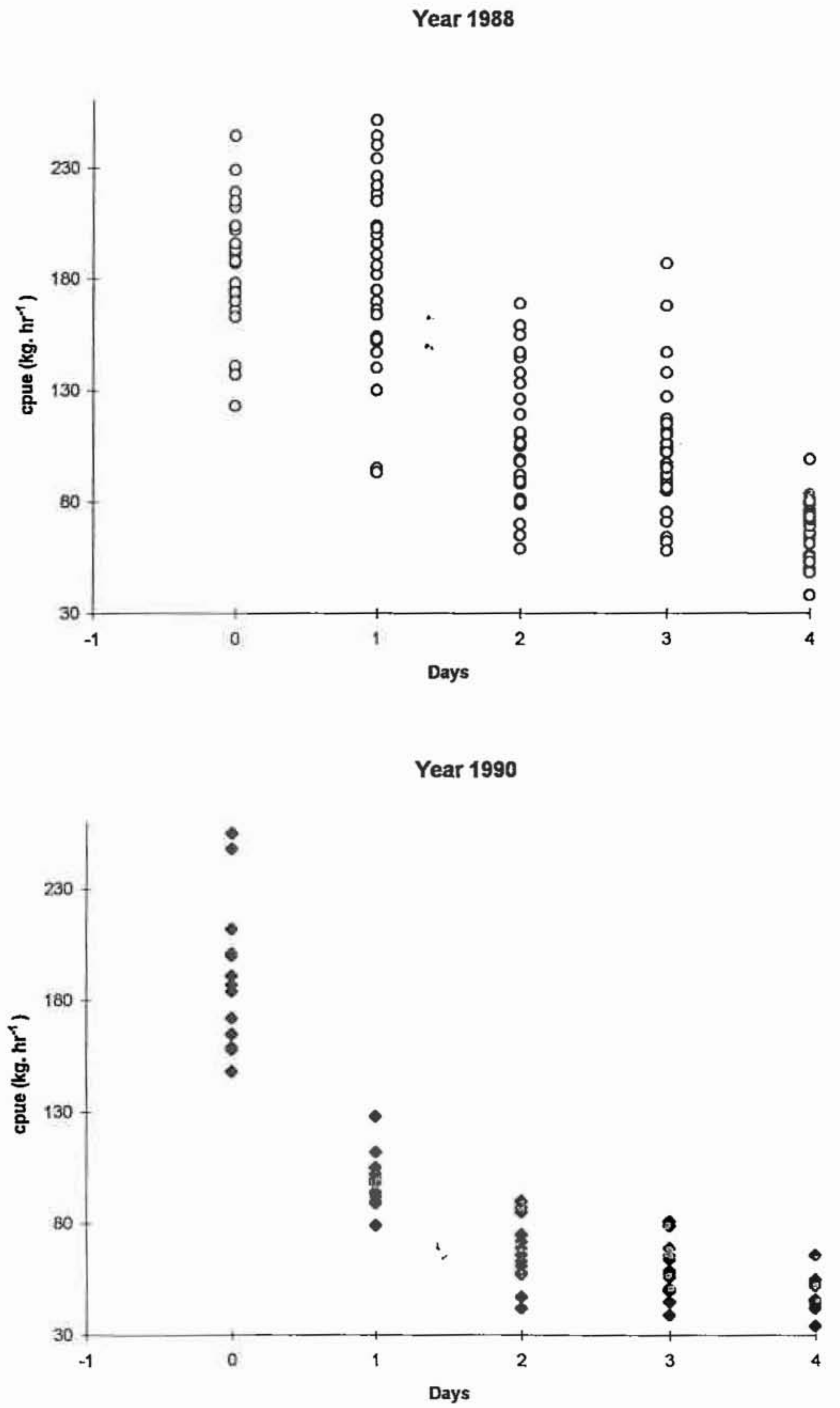
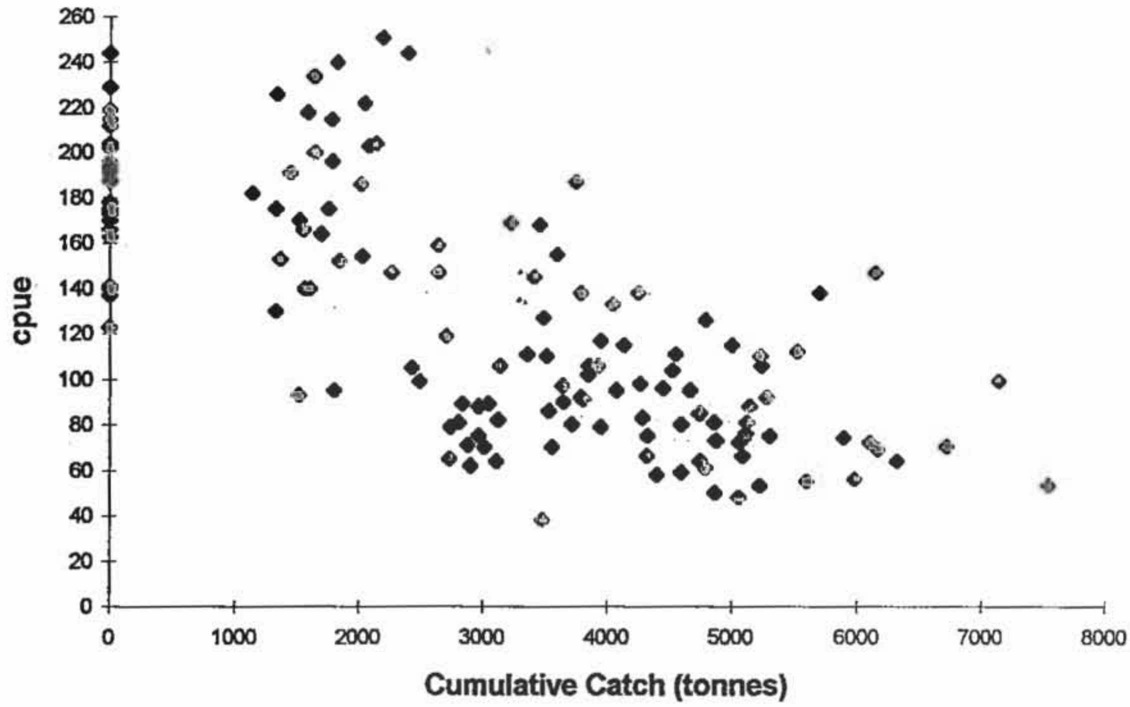


Figure 18a: Depletion comparisons between 1988 and 1990.

Year 1 - 1988.



Year 2 - 1990.

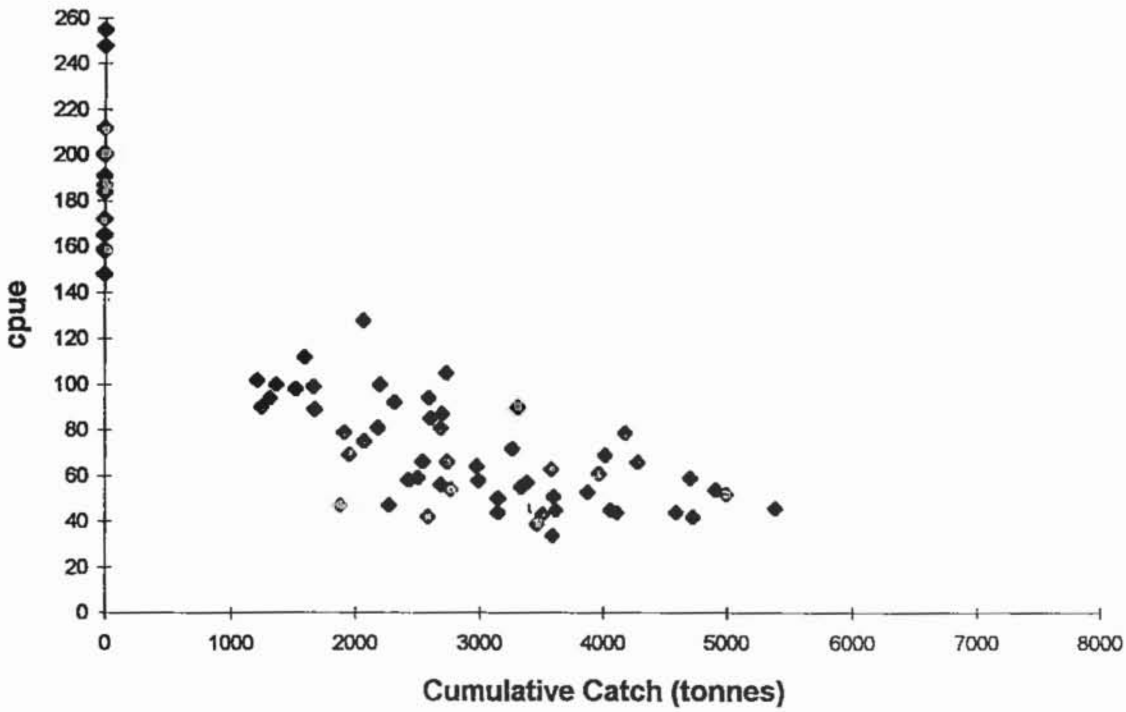


Figure 18b: Depletion comparisons in 1988 and 1990.

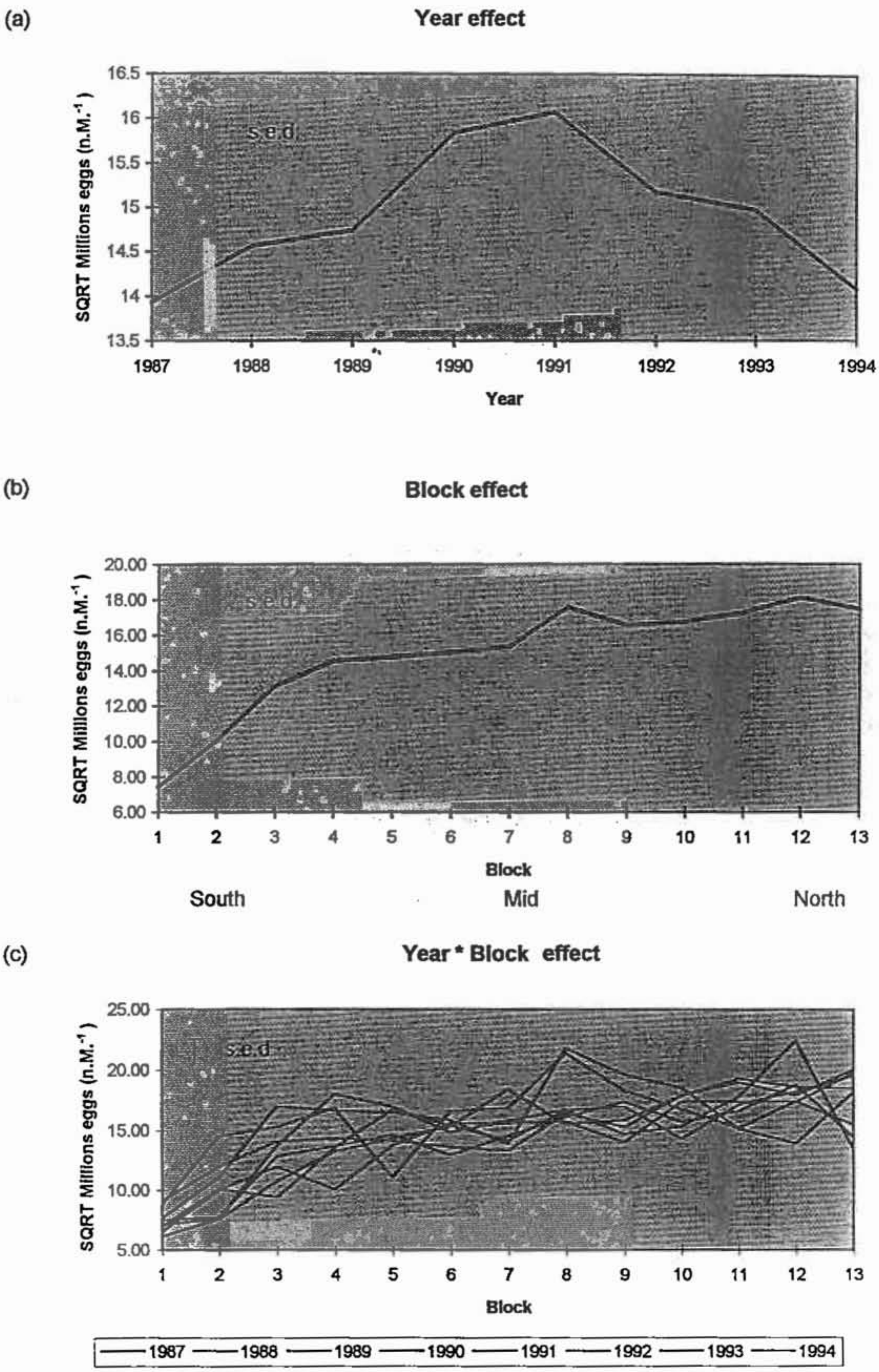


Figure 19: ANOVA of egg production over 8 years and 13 spatially separated regions or Blocks in Spencer Gulf.

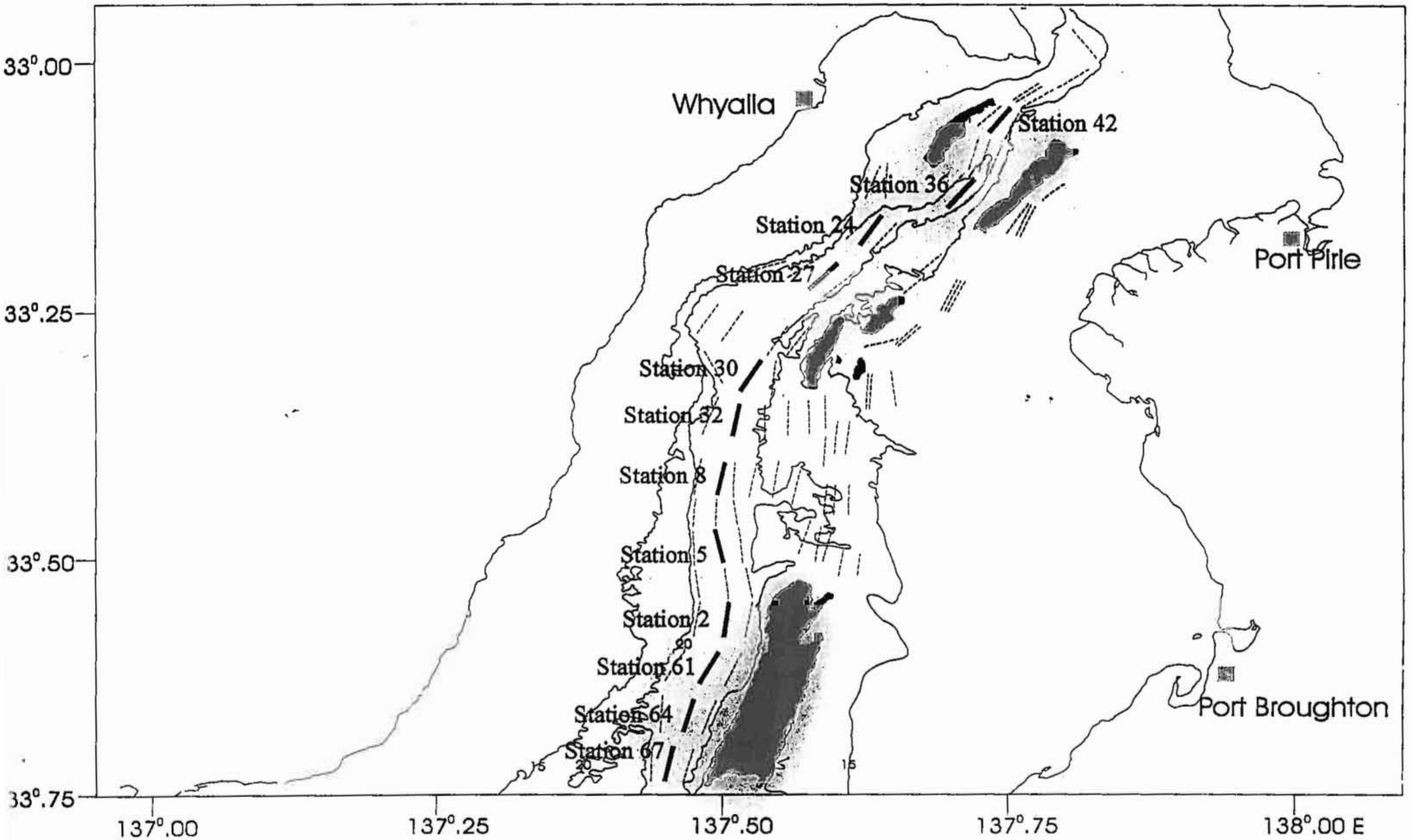


Figure 20a: Layout of mid channel sampling stations in Spencer Gulf.

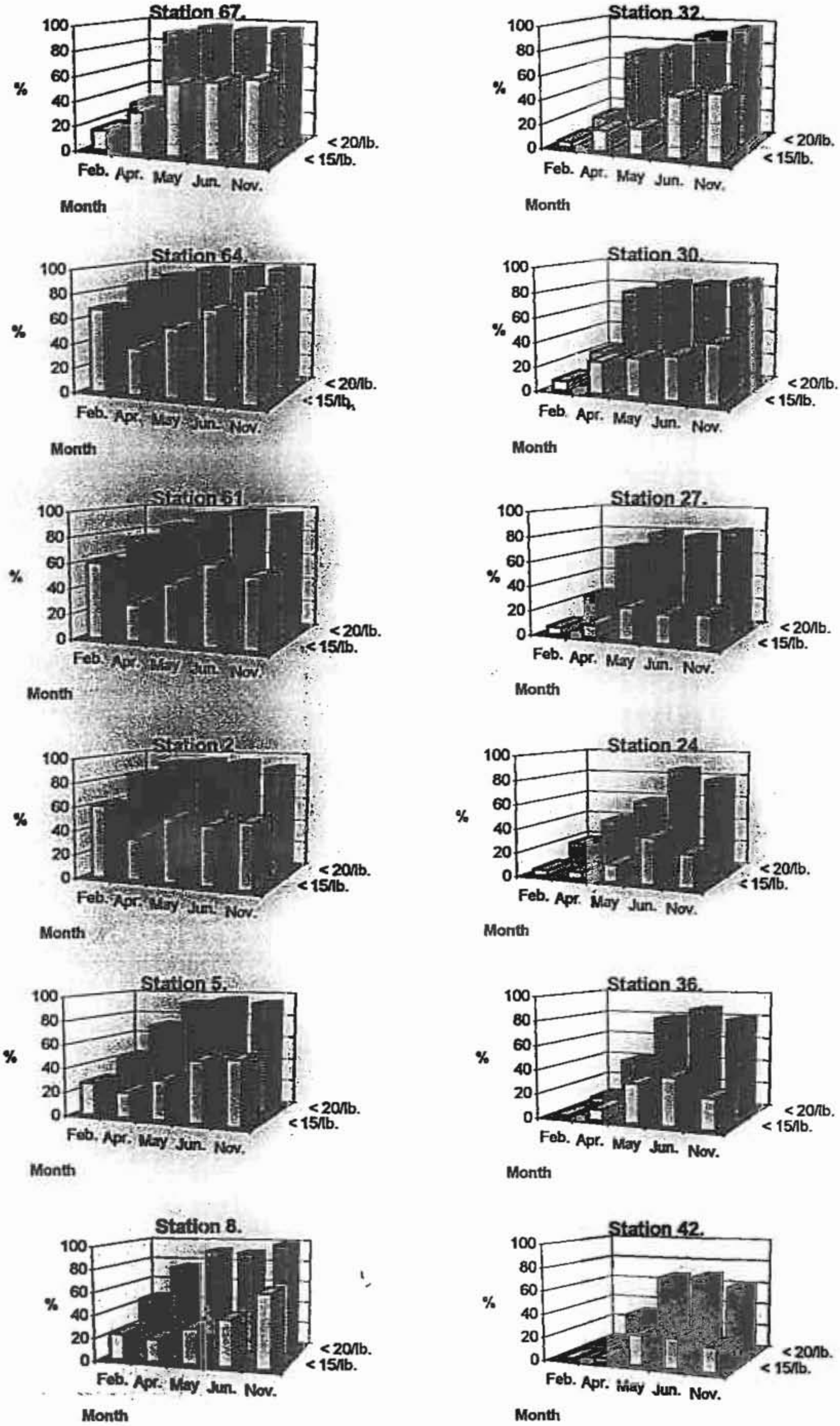


Figure 20b: Percent commercial size of prawns along a latitudinal gradient in Spencer Gulf from February to November 1988. Grade is percentage less than 20/lb and 15/lb (head-on).

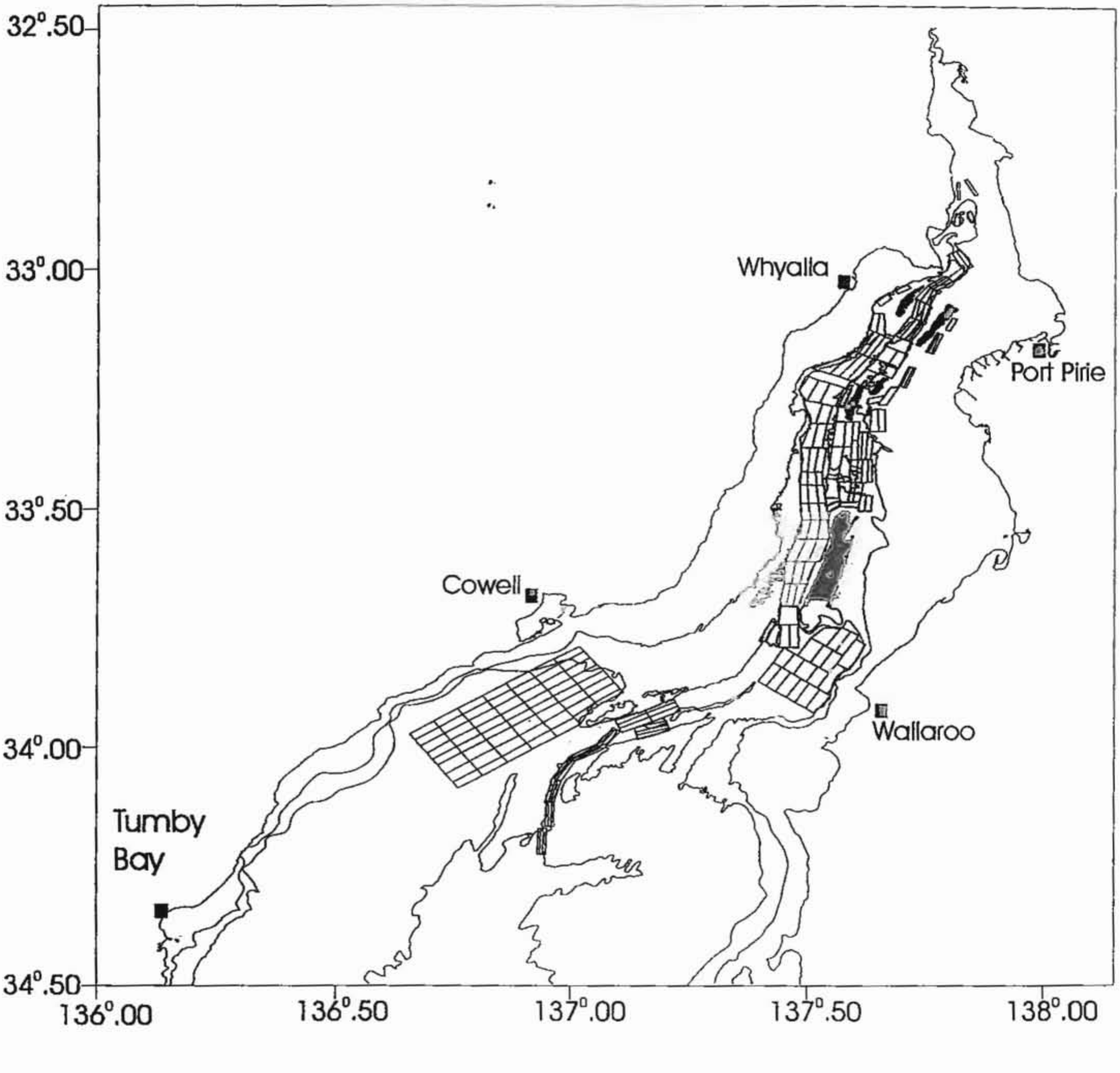


Figure 21: Geographical Systems (GIS) layout of trawl sampling blocks or spatial units in Spencer Gulf.

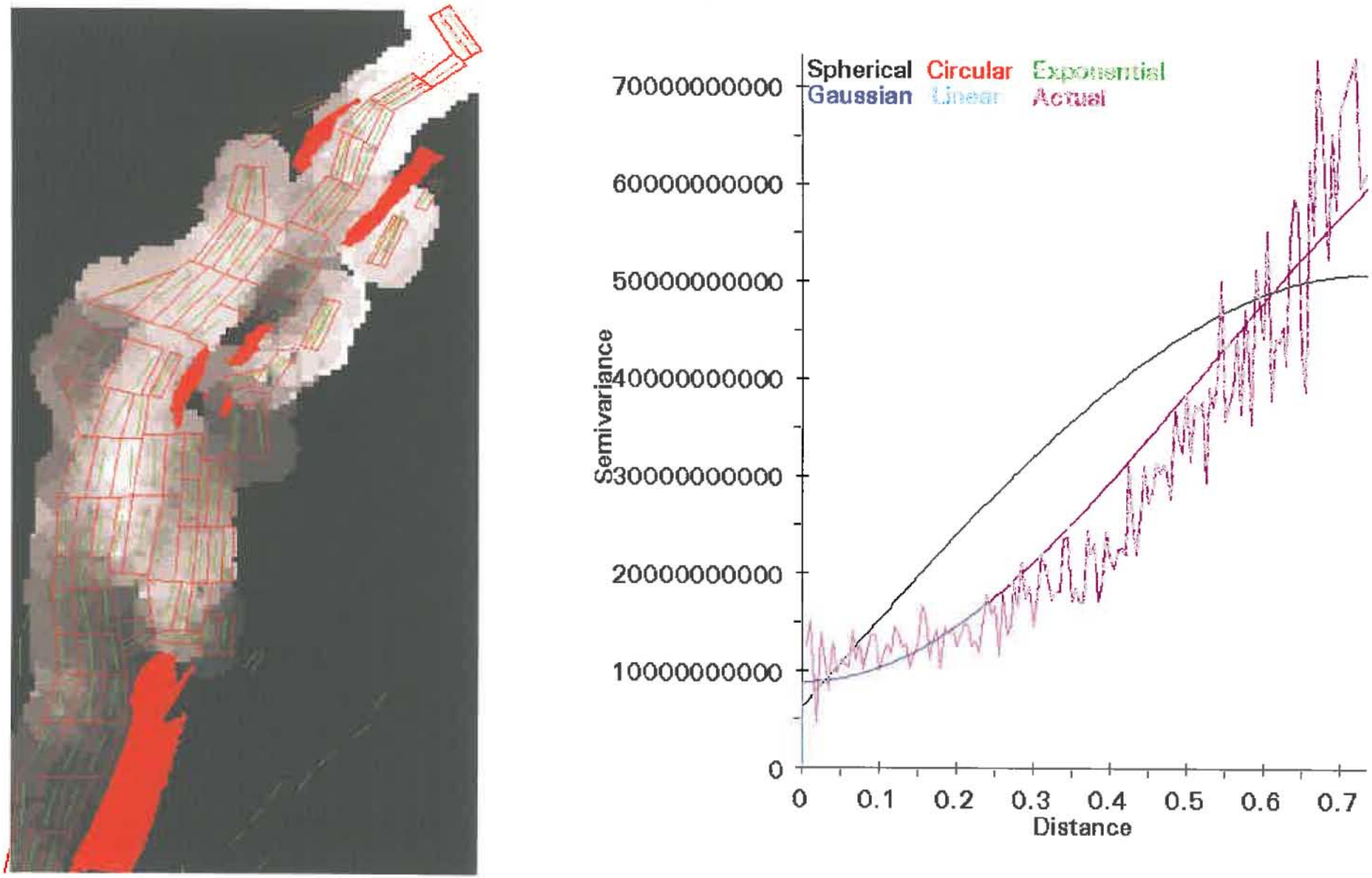


Figure 21.2. Egg production spatial pattern, February 1988. Semi-variogram plots using gaussian and spherical models and output from kriging using a gaussian model.

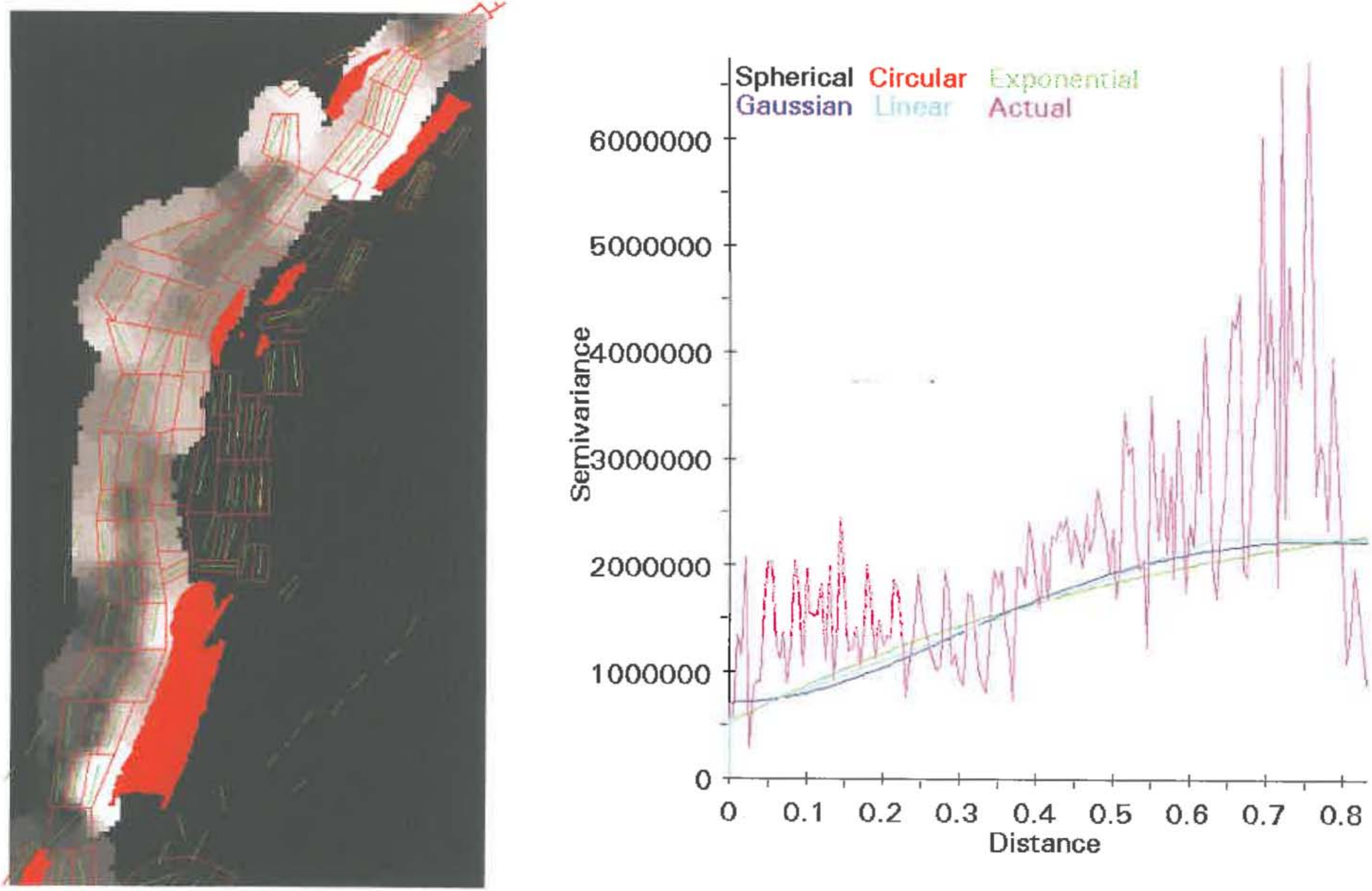


Figure 21.3. Egg production spatial pattern, April 1990. Semi-variogram plots using gaussian and spherical models and output from krigging using a gaussian model.

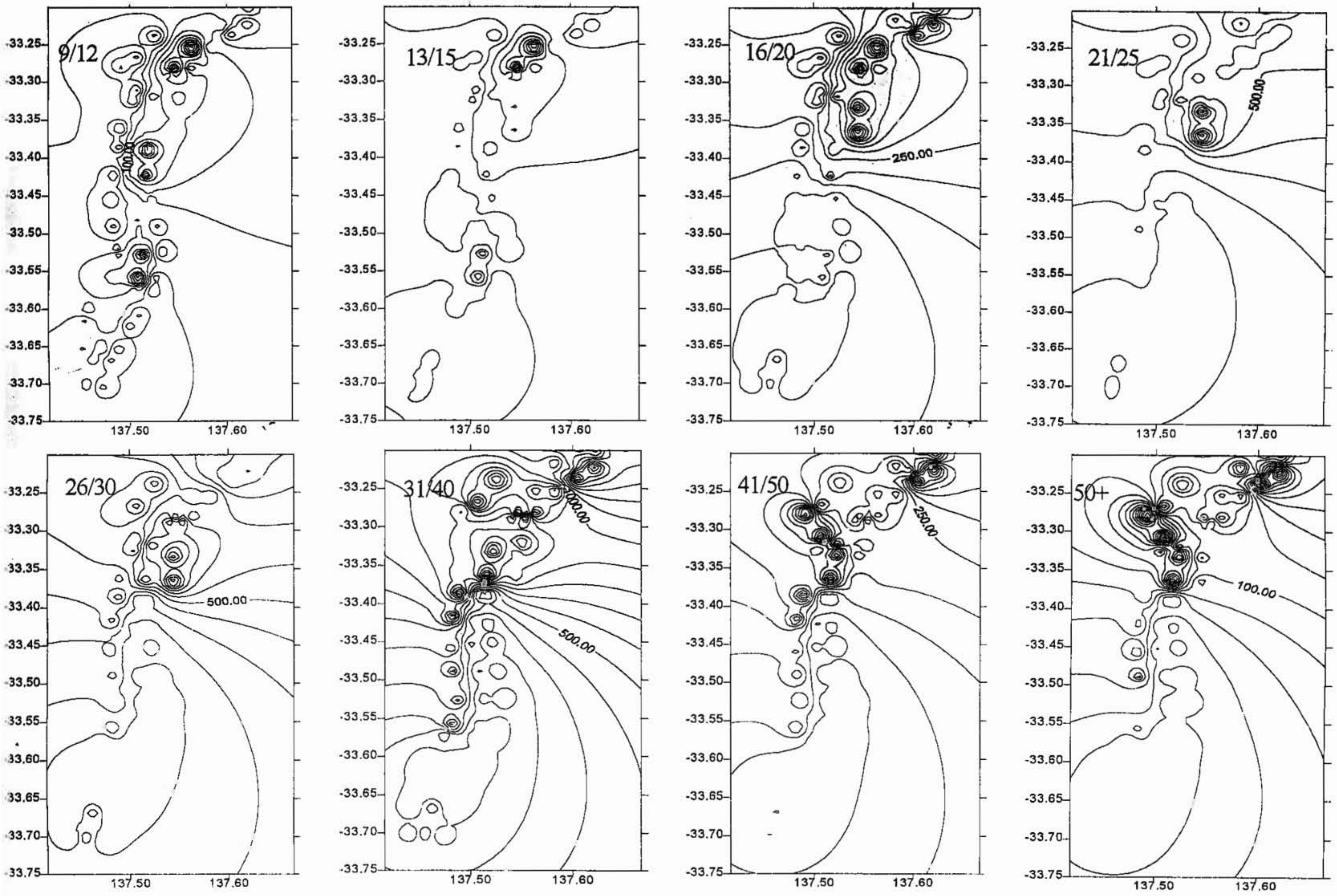


Figure 21.4: Surface contour plots of prawn grades (9/12 to 50+ lb head-on) in the Northern Spencer Gulf, April 1988

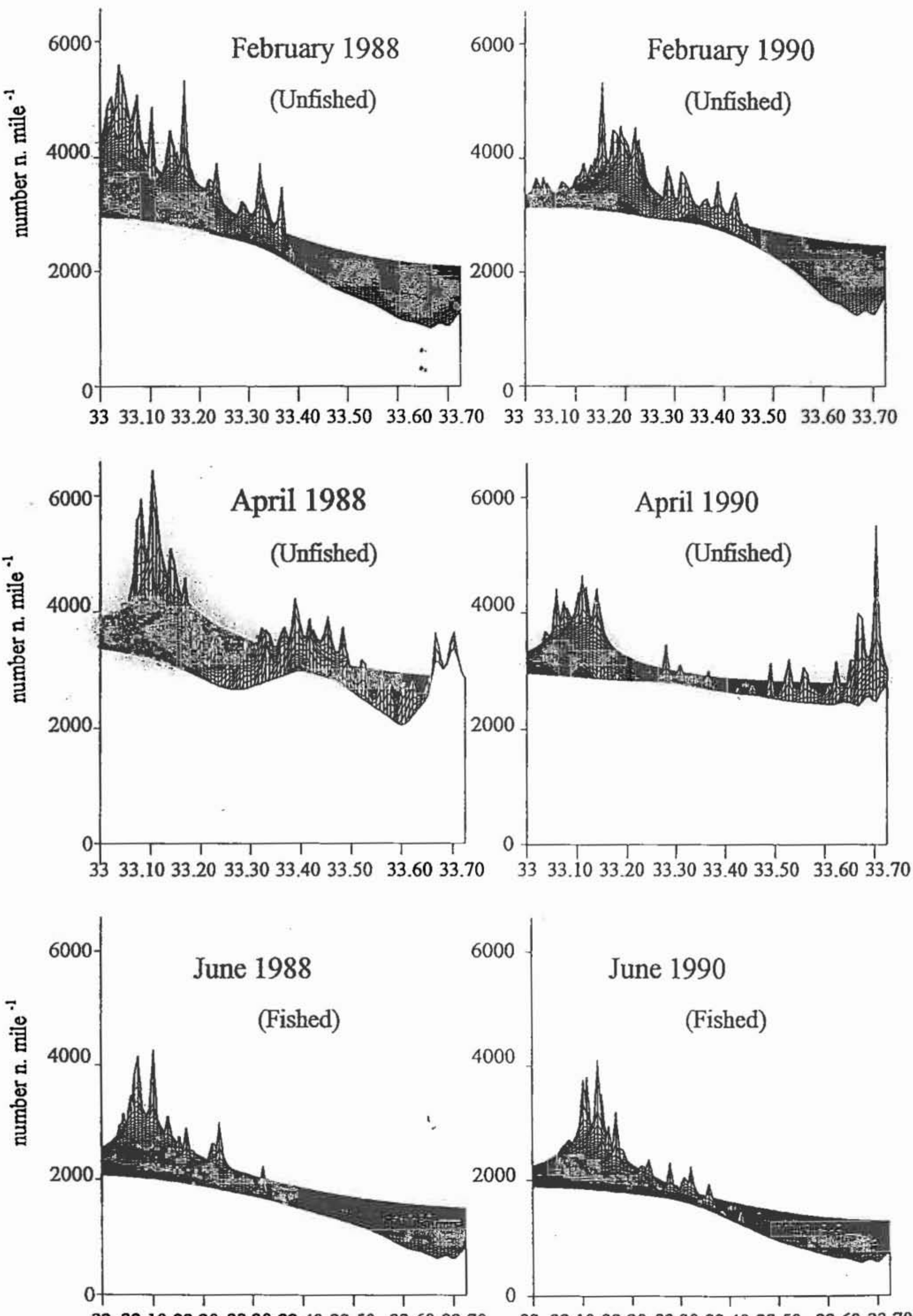


Figure 22: Comparison of numbers of P. latisulcatus in northern Spencer Gulf and the effect of fishing.

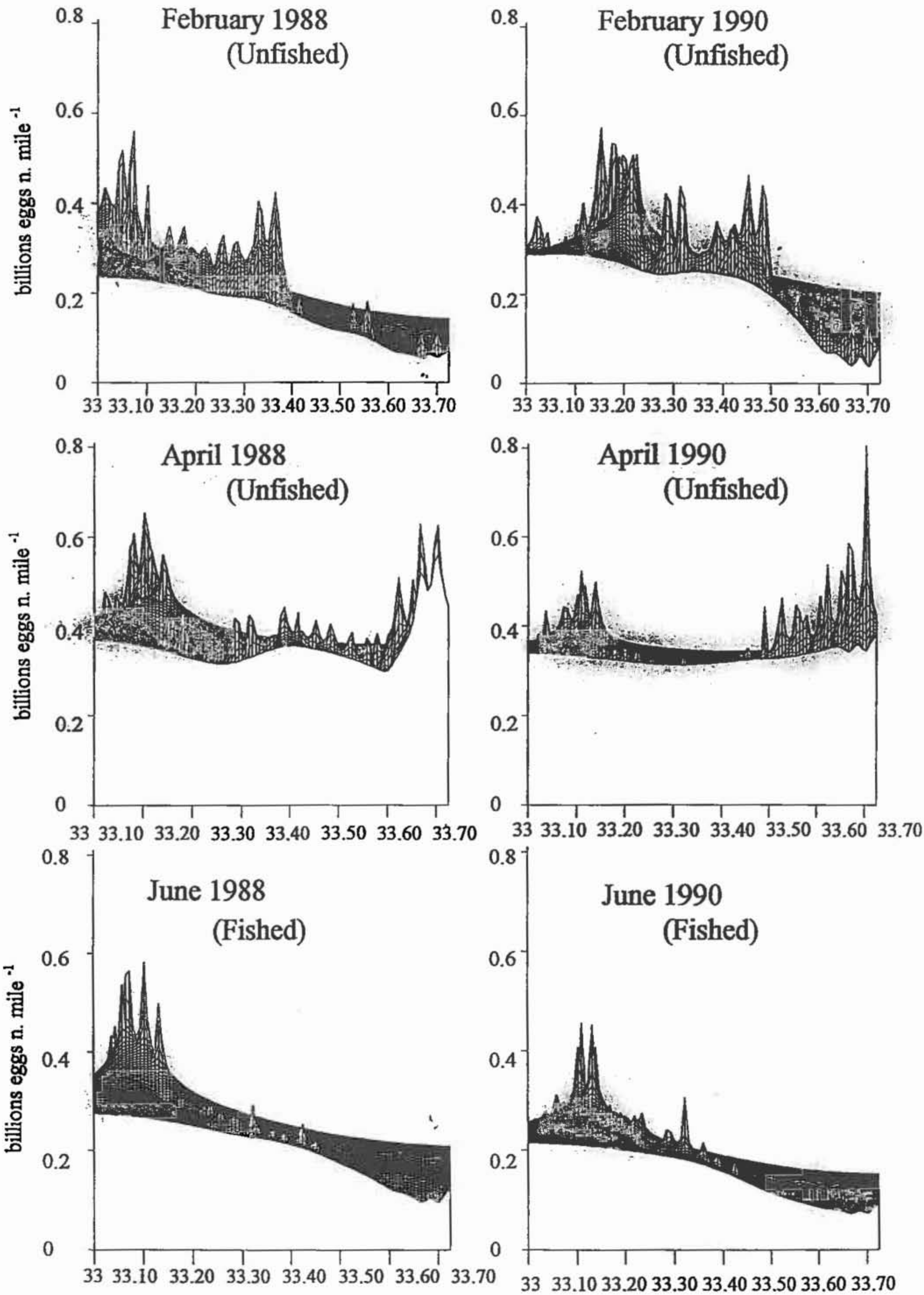


Figure 23: Comparison of potential egg production in P. latisulcatus in northern Spencer Gulf and the effects of fishing.

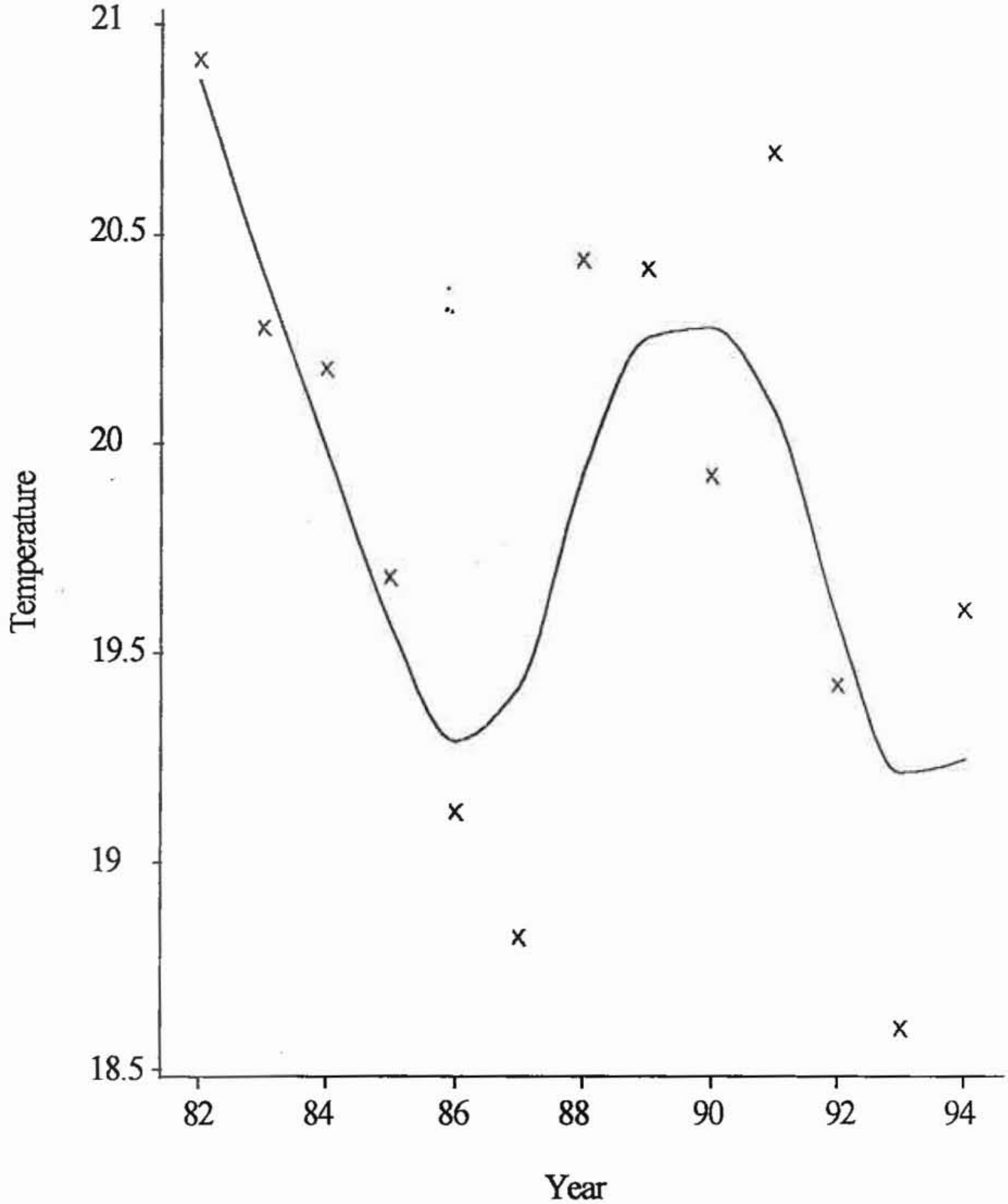


Figure 24: Mean air temperature trends over July - December, 1982 - 1994 at Whyalla.

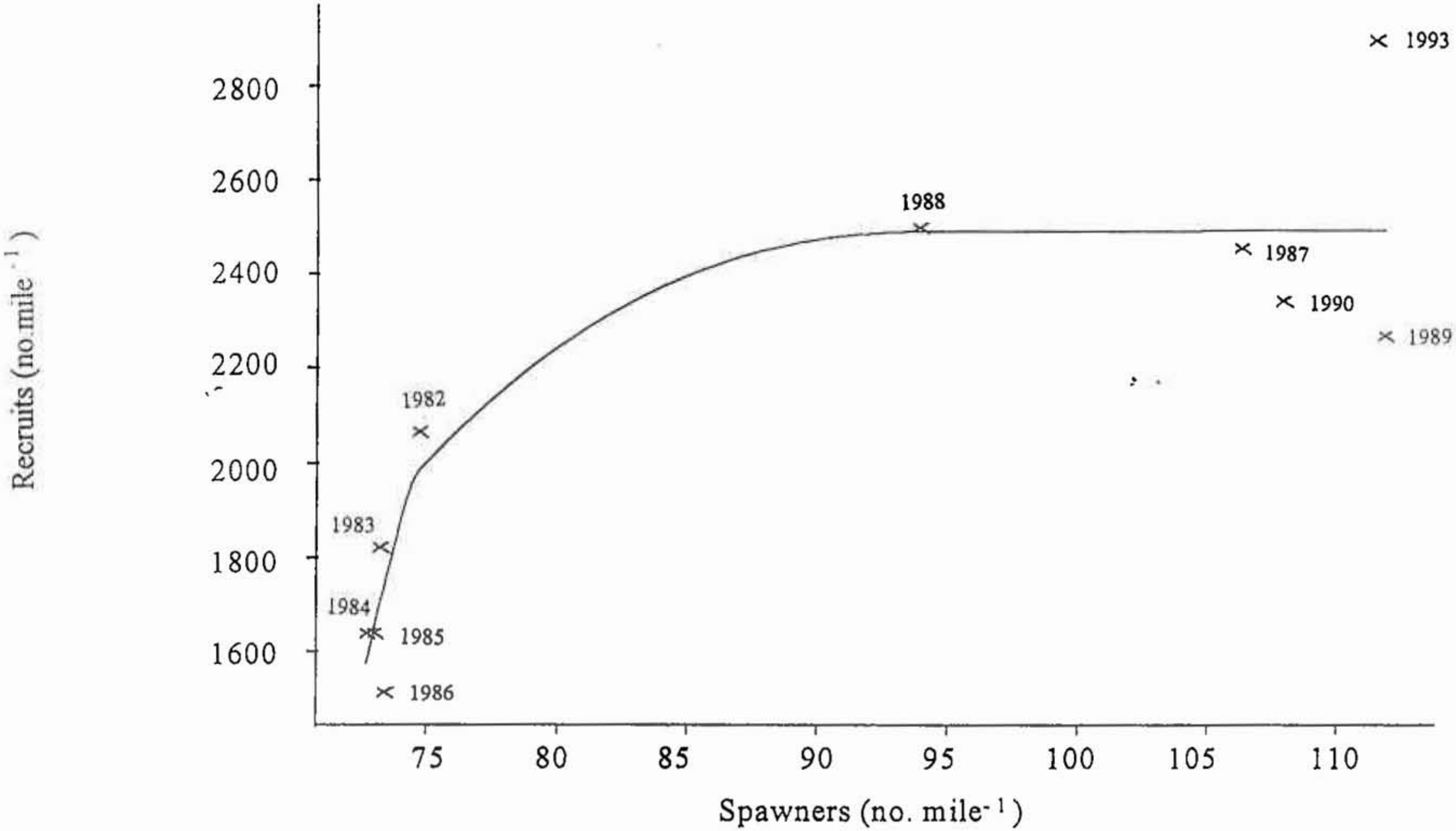


Figure 25: The relationship between spawners and recruits in Northern Spencer Gulf. Spawners are female prawns > 42 mm CL.

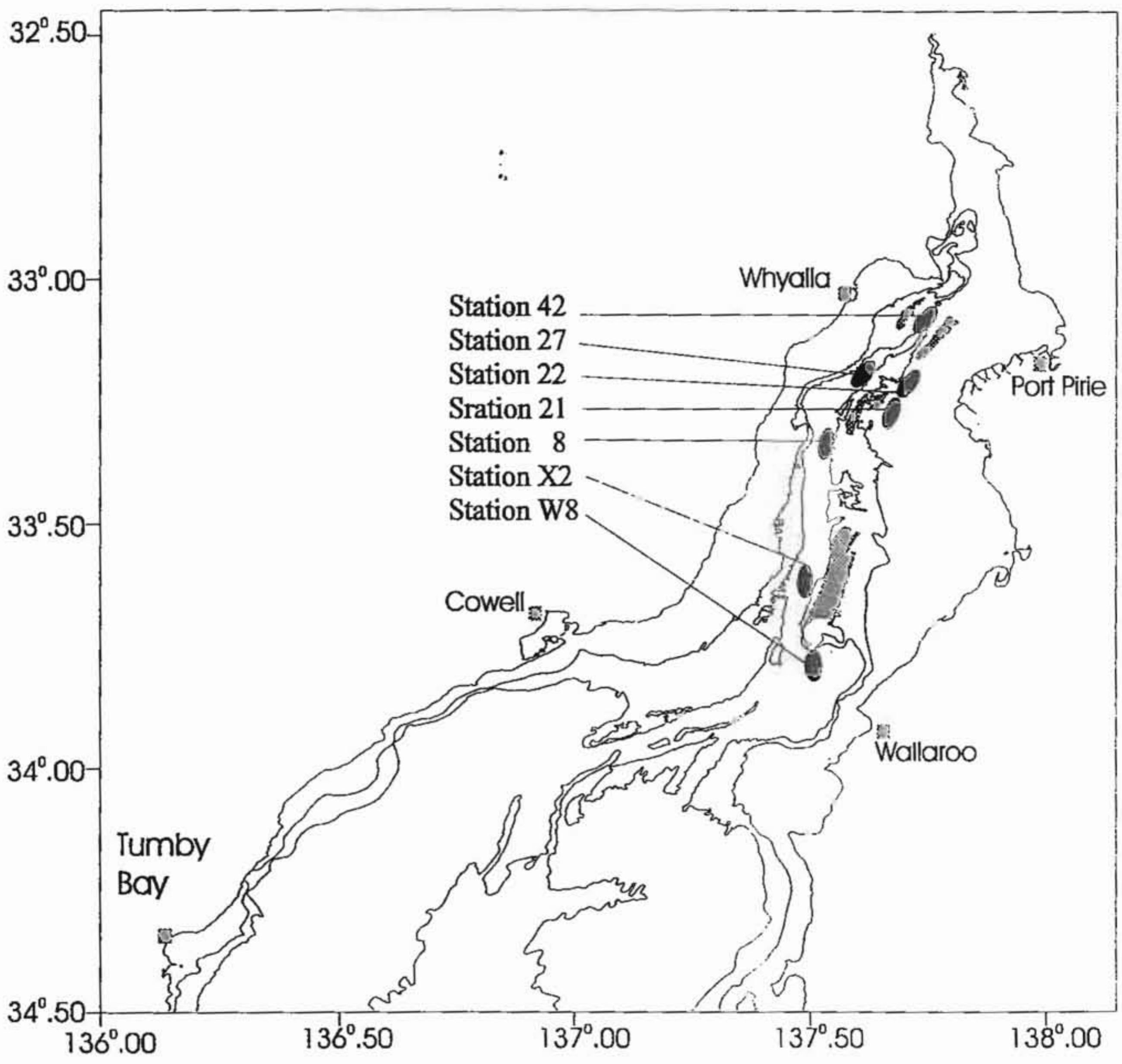


Figure 26: Sampling sites for monitoring female prawn reproductive dynamics in Spencer Gulf.

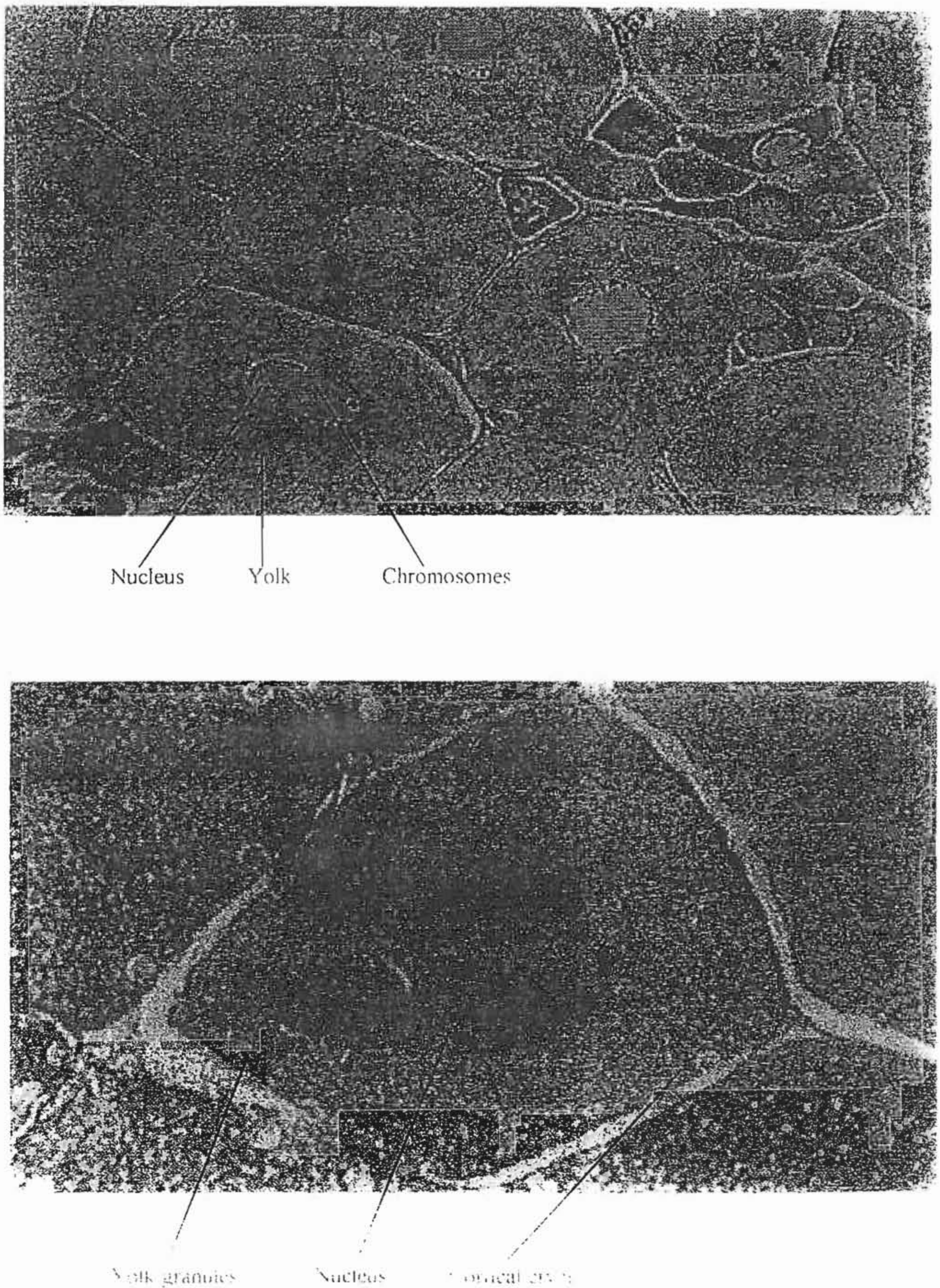


Figure 27 Transverse sections of P. latisulcatus gonad, showing [illegible] using H and E stain (source SARDI FRDC)

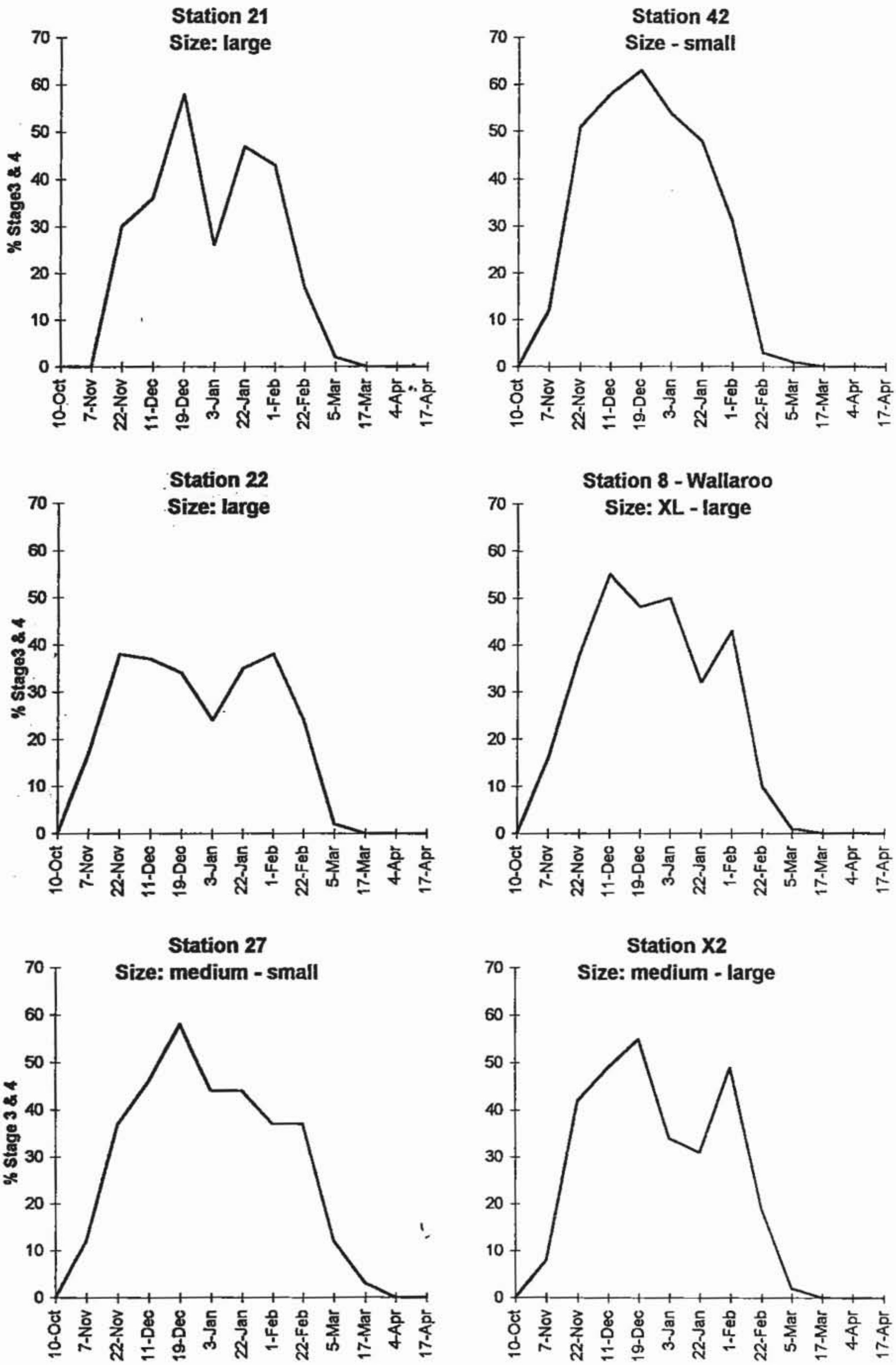


Figure 28: Spatial trends in the maturity status (stage 3 & 4) of female
P. latisulcatus in Spencer Gulf.

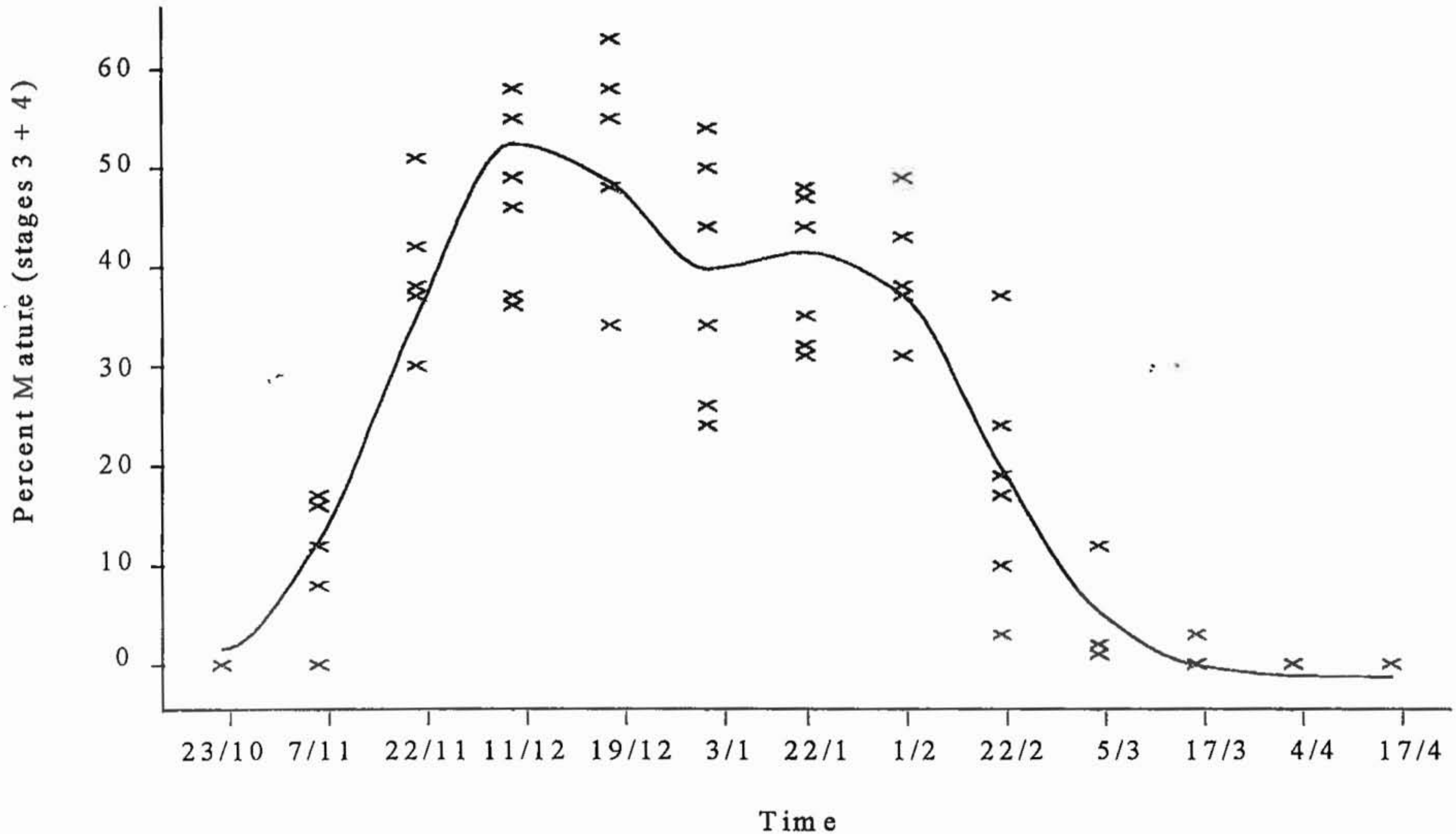


Figure 29: Female P.latisulcatus maturity over 1992-1993 fitted to a double gaussian model pooling data from six sampling sites in Spencer Gulf

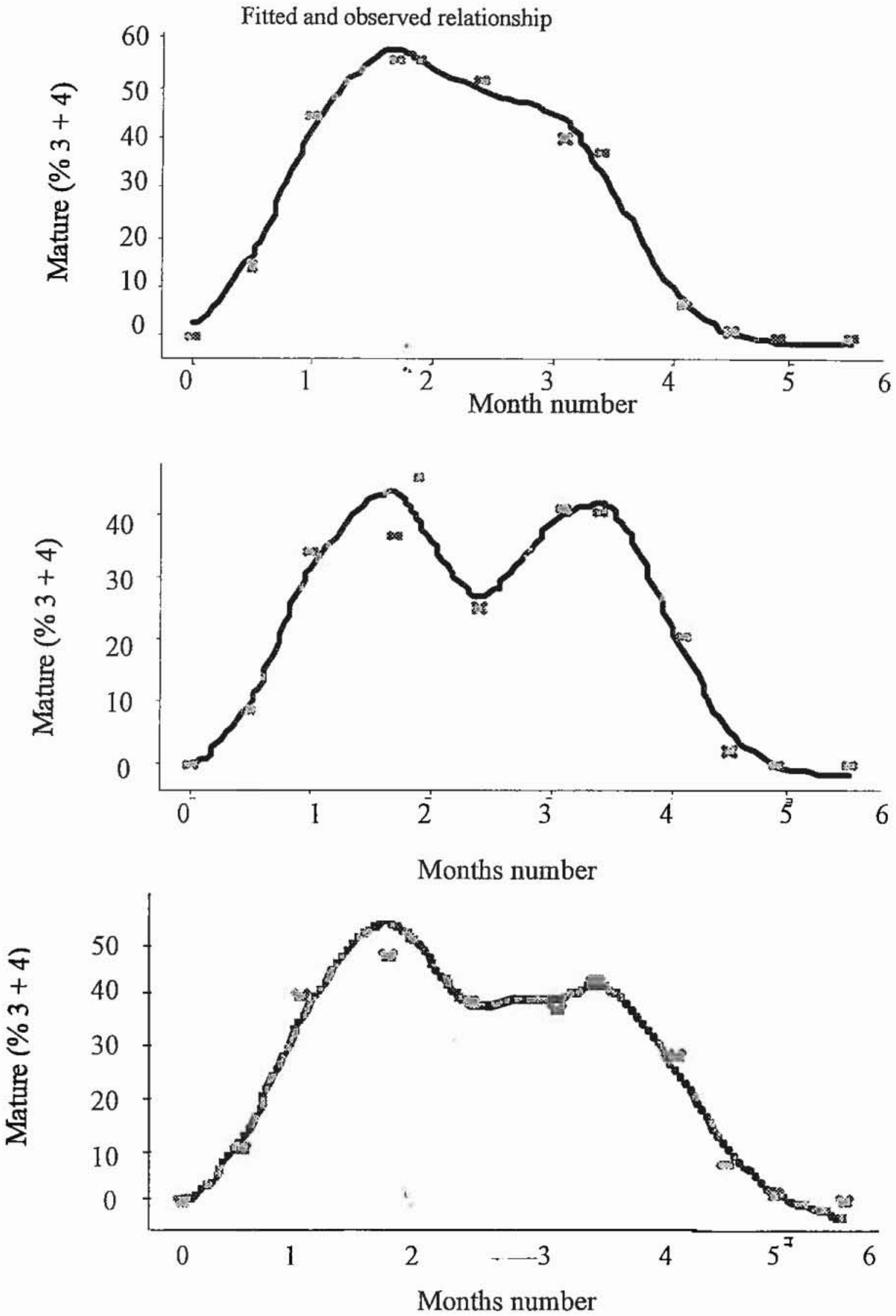


Figure 29.2: Double Gaussian fits to female prawn maturity data based on stages 3 + 4; a - Region 1, b - Region 2, c - Region 3.

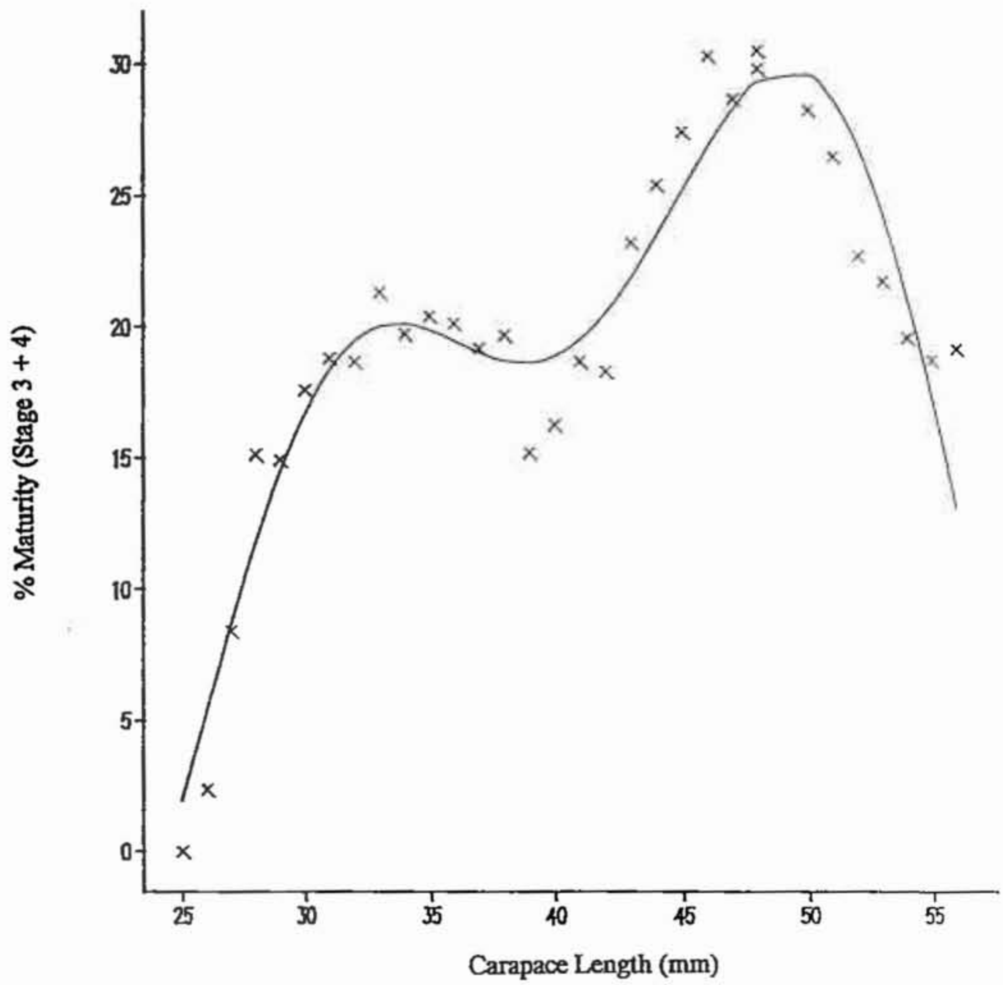


Figure 30: The relation ship between size and the percentage of female P. latisulcatus at ripe (or stage 3 + 4) maturity stage in Spencer Gulf.

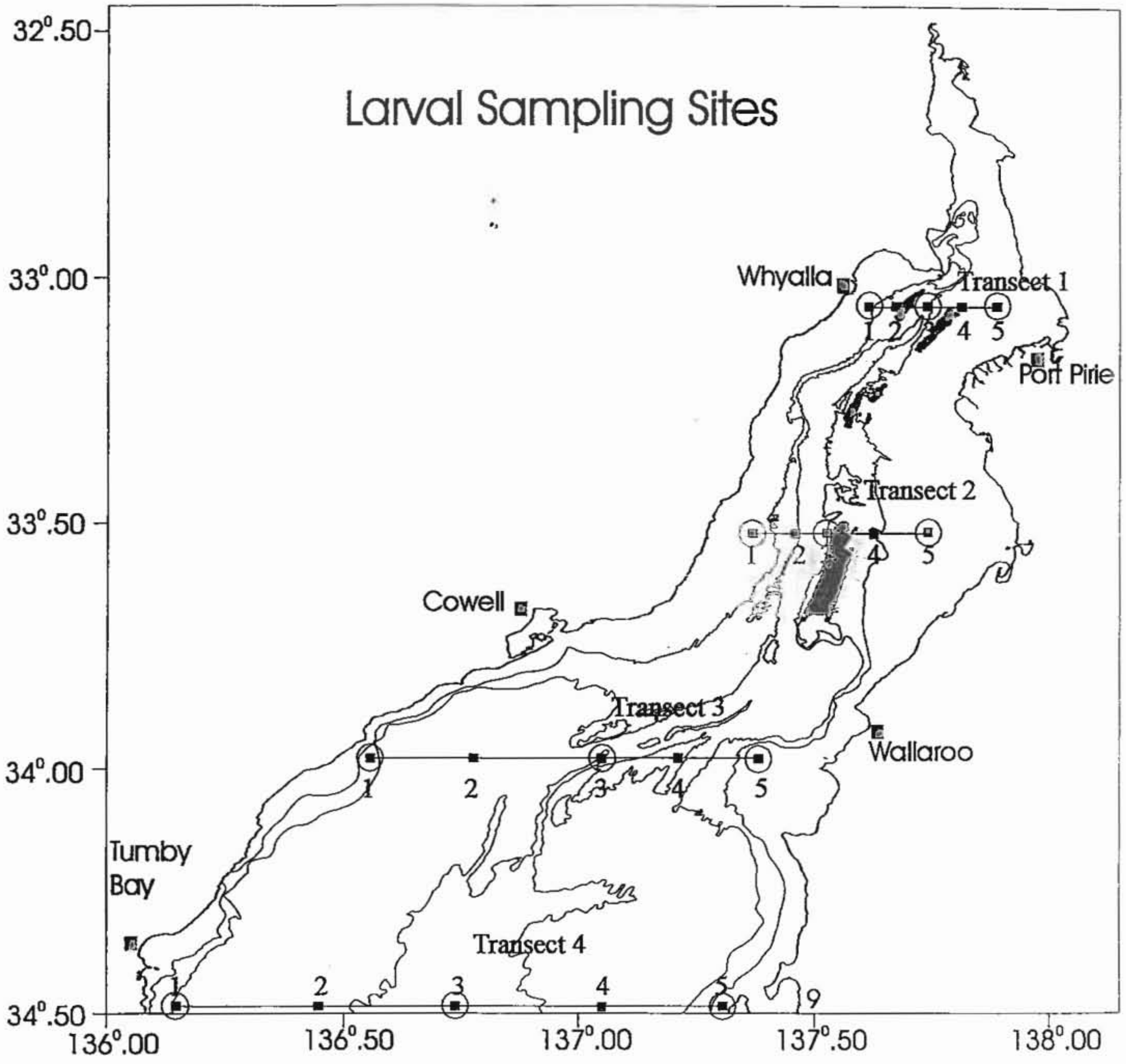


Figure 31: Penaeus latisulcatus larval sampling sites in Spencer Gulf. Comparisons were made of stations 1, 3 and 5 over each Transect from North (Transect 1) to South (Transect 4).

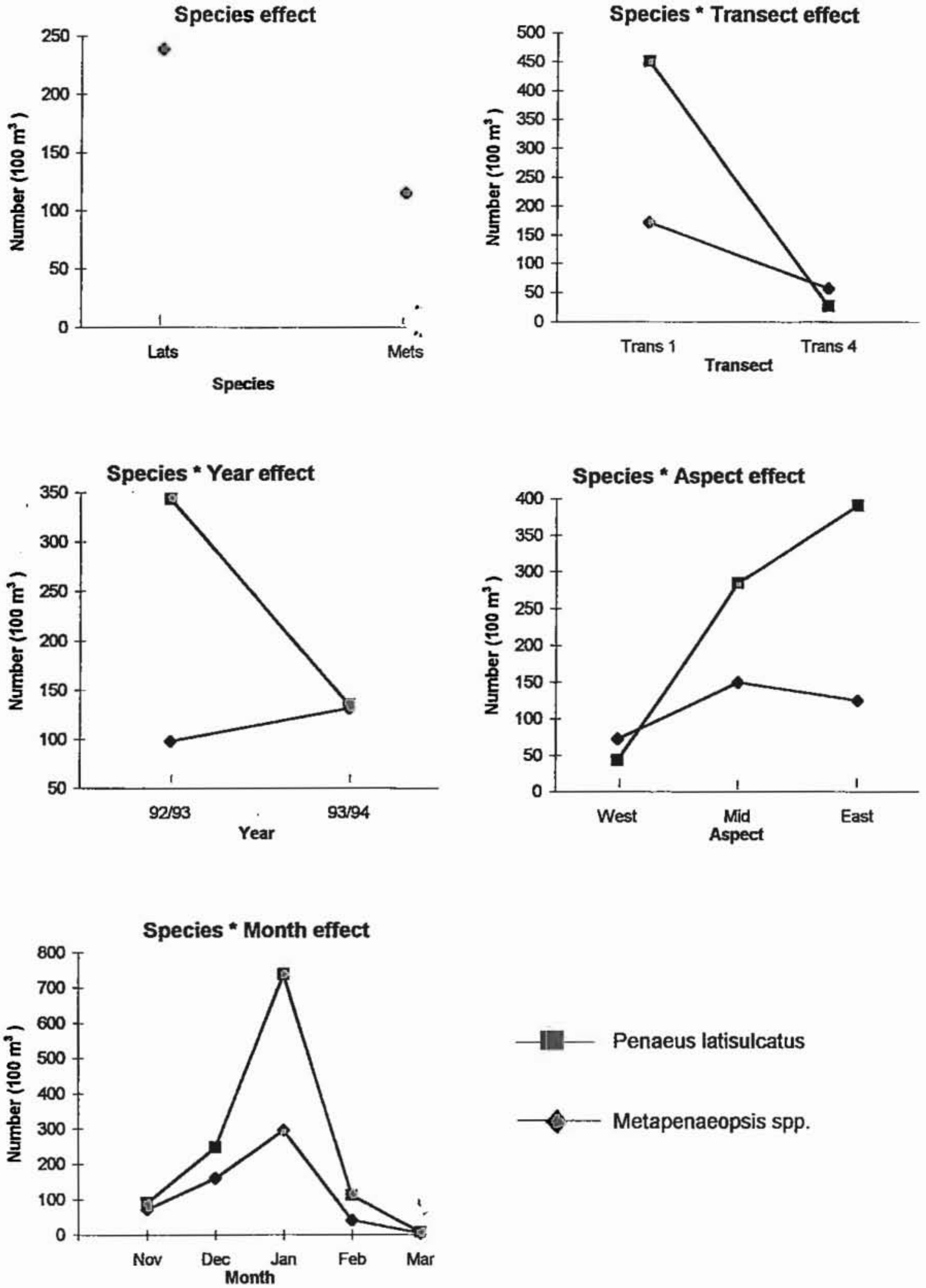
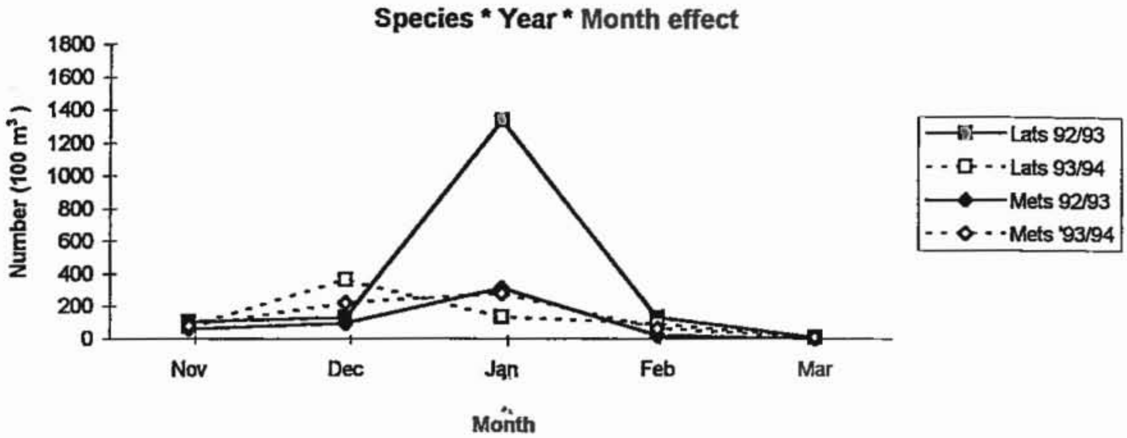
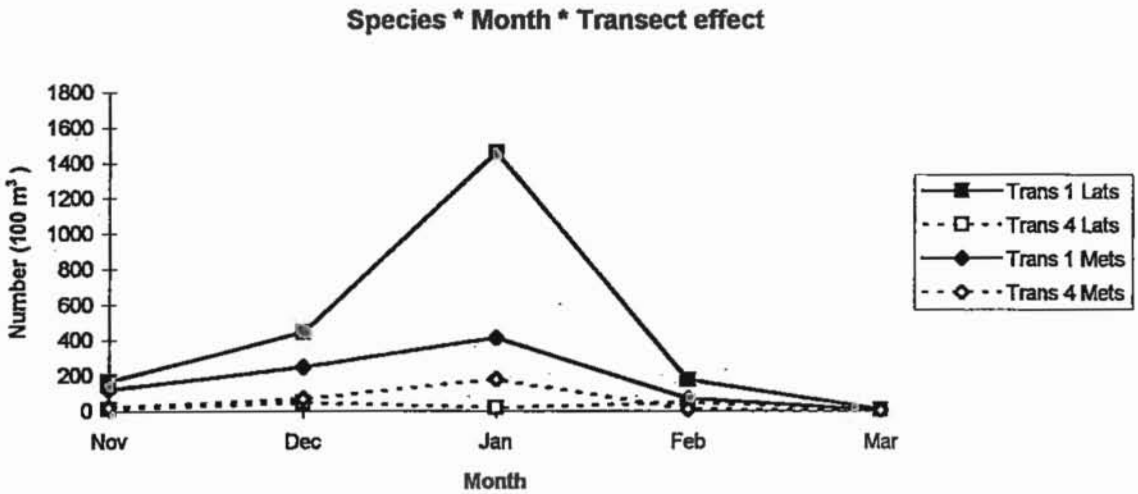


Figure 32: Comparison of larval Penaeus latisulcatus and Metapenaeopsis spp. numbers over two Transects (North and South), sides of Gulf (Aspect) and Month during 1992/93 and1993/94.





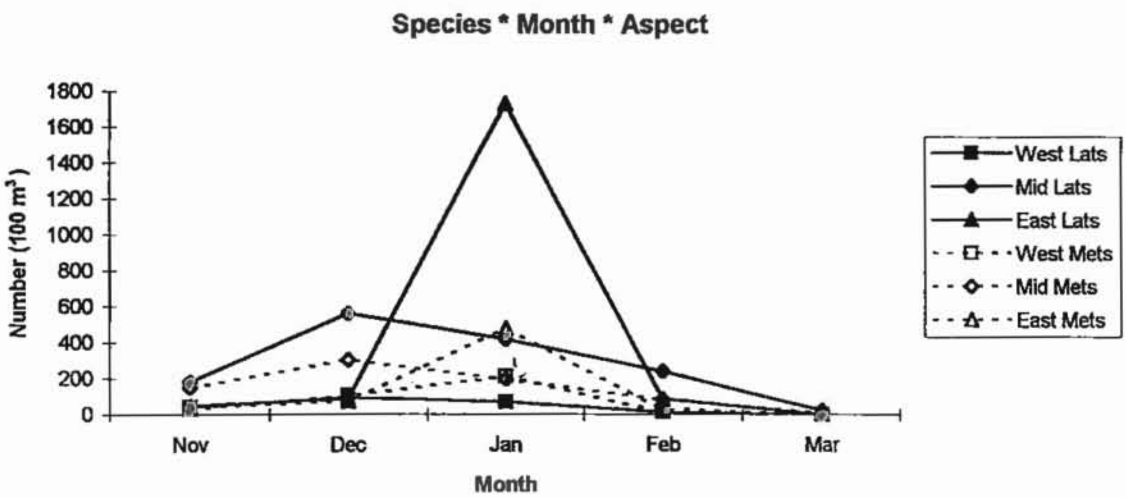


Figure 33: Comparisons of trends in larval P. latisulcatus and Metapenaeopsis spp in Transect 1 (North) and Transect 4 (South) from November - March, 1992/93 and 1993/94.

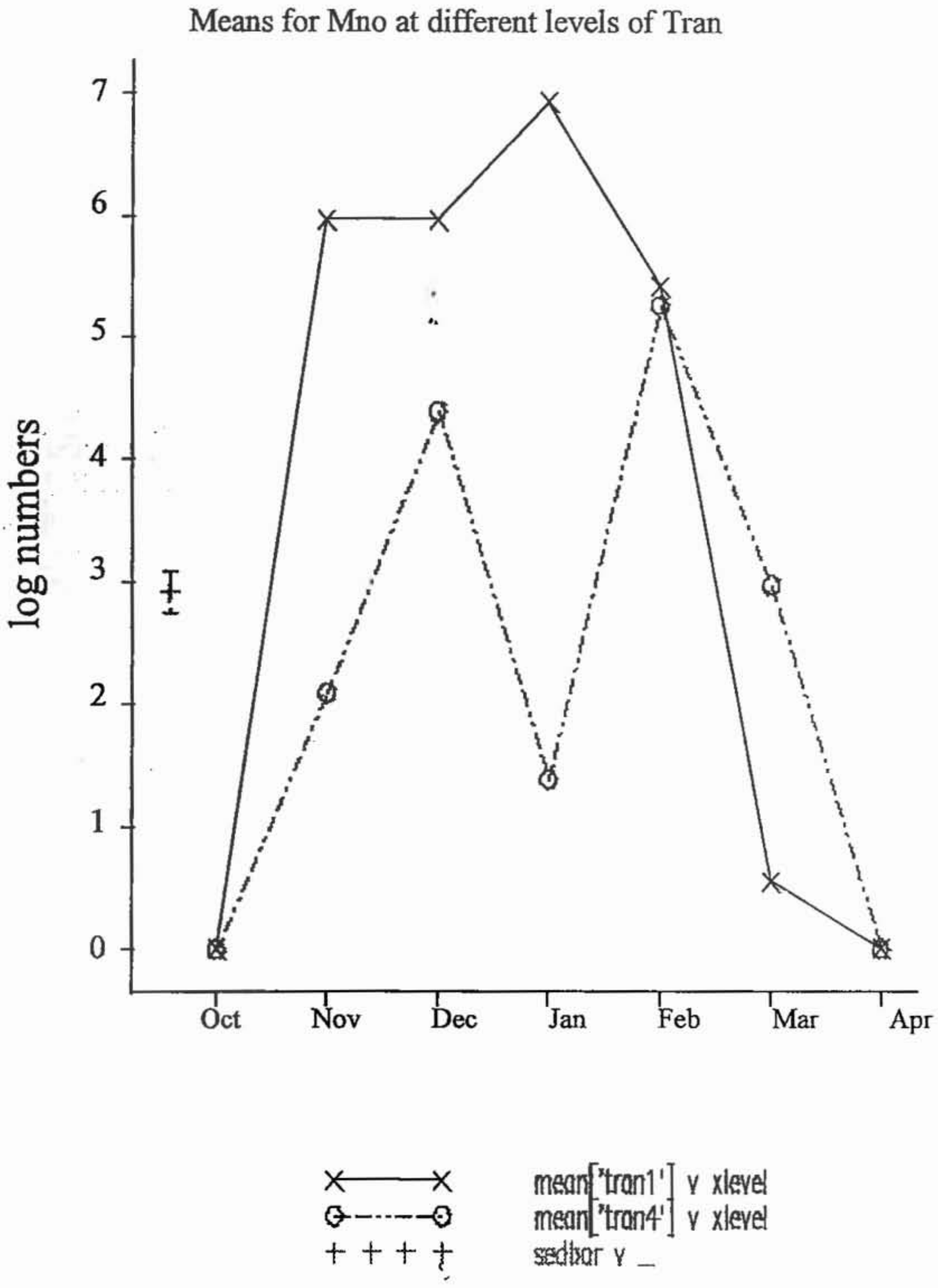


Figure 33.1: Mean number (log transformed) of zoea 1 and 2 over Transects 1 and 4 from October 1992 to April 1993.

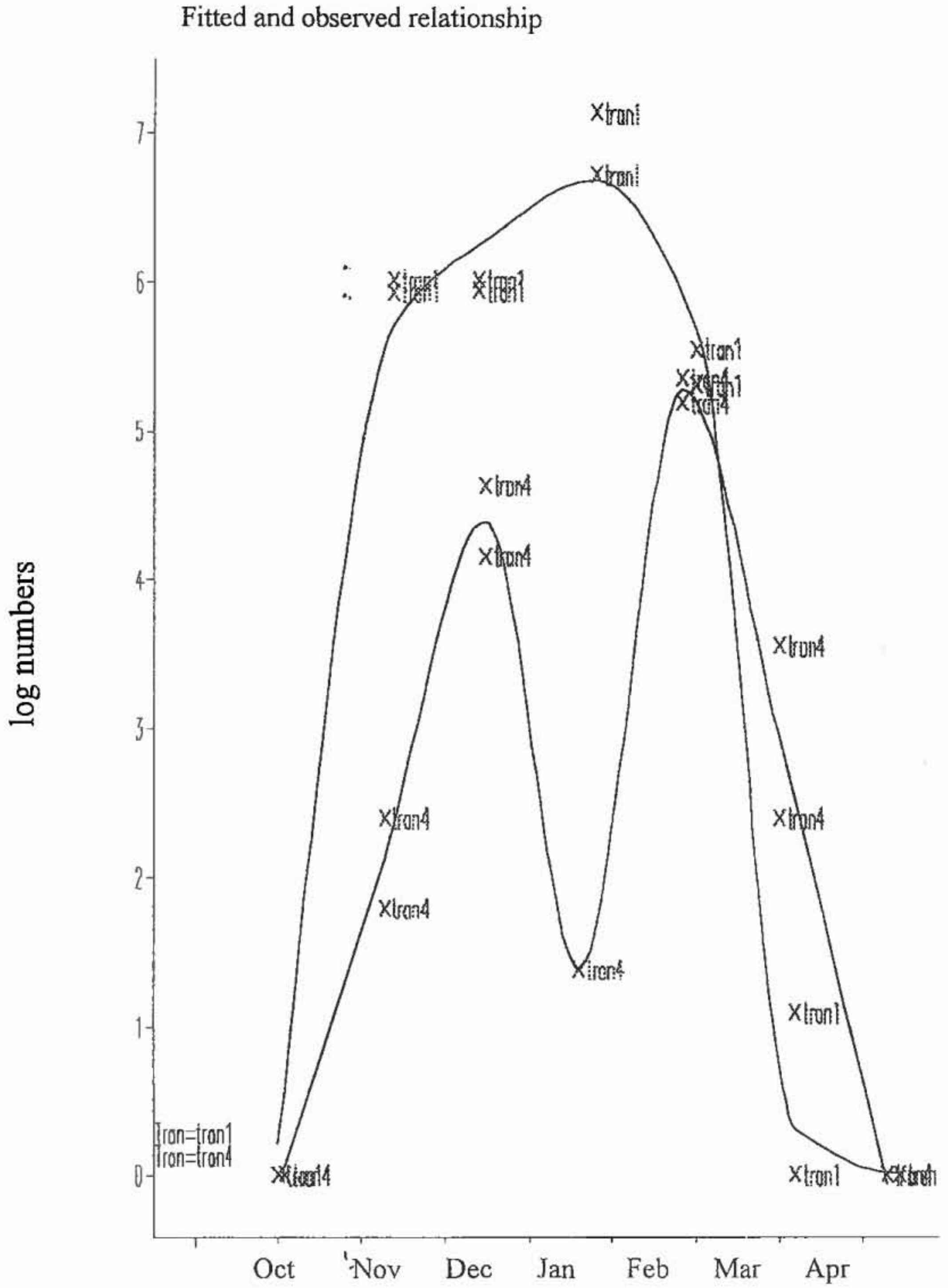


Figure 33.2 : P.latisulcatus larval (zoea 1 + 2) trends in Spencer Gulf. Data fitted to double Fourier regression models illustrating, peaks in maturity and differences in maturity phases between Transect 1 and Transect 4.

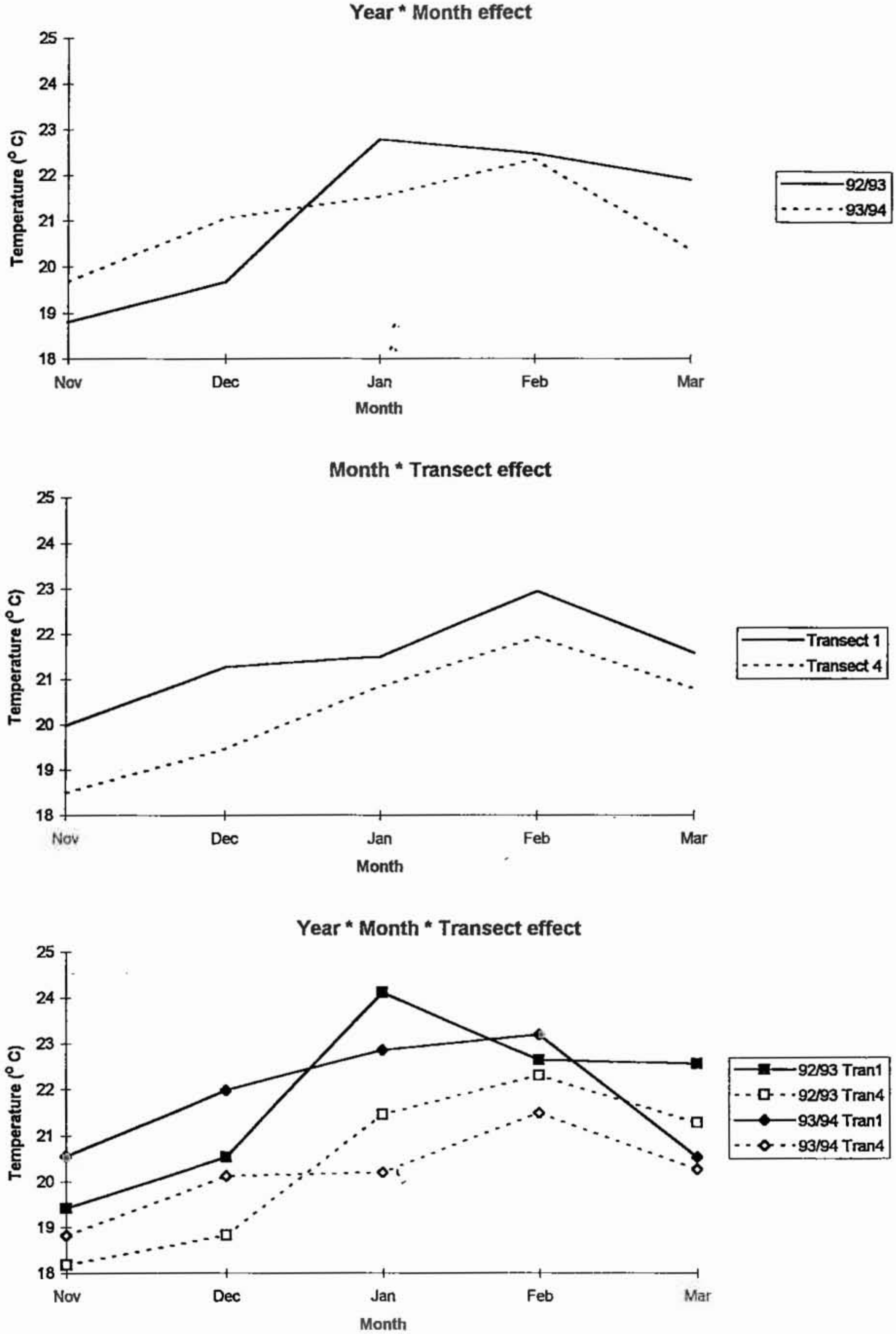


Figure 34.1: Trends in water temperature across Transect 1 (North) and Transect 4 (South) in Spencer Gulf over 1992/93 and 1993/94.

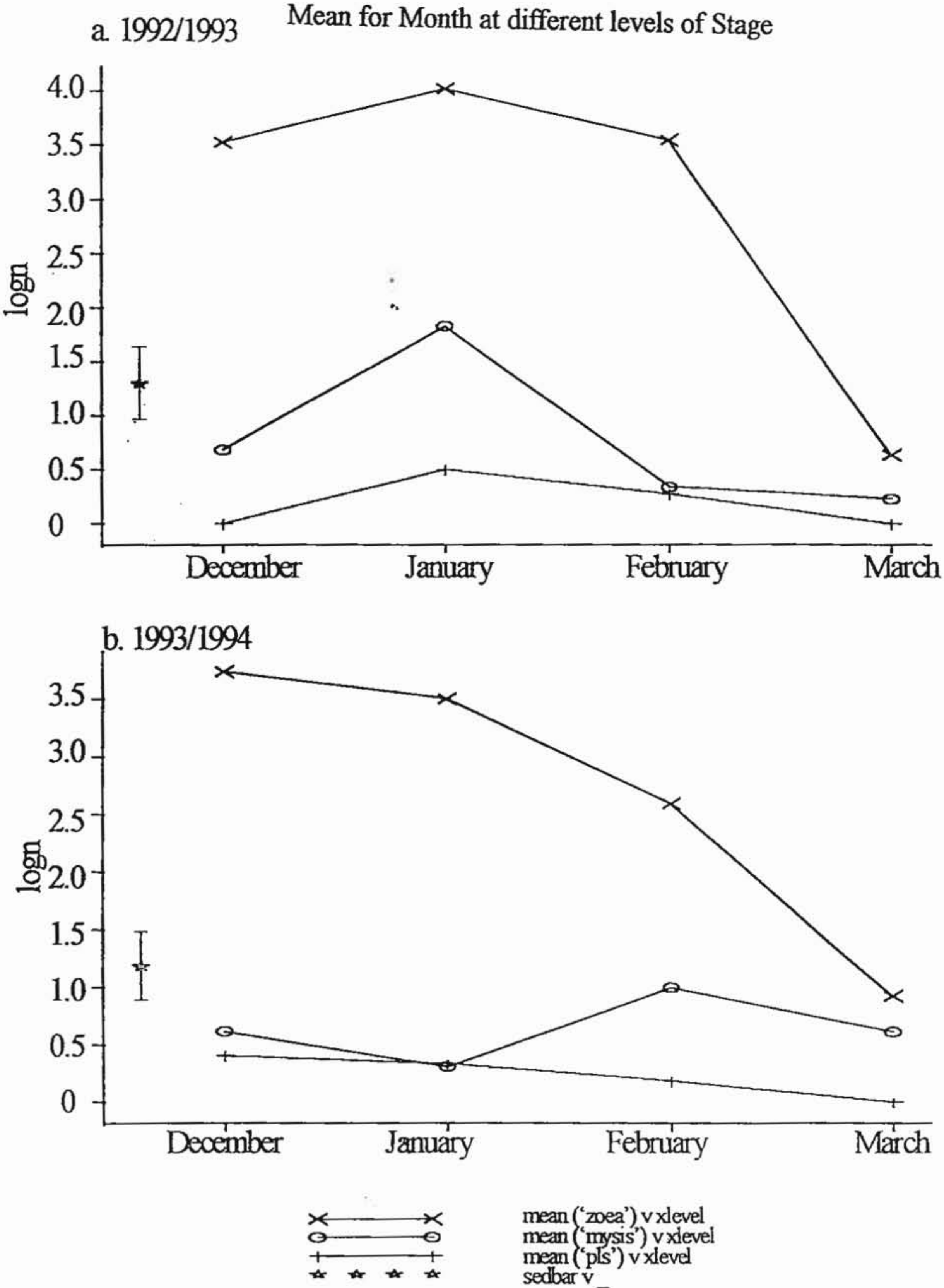


Figure 34.2: Trends in numbers (logn) of P.latisulcatus zoea, mysis and post larvae; a- 1992/93; b- 1993/94.

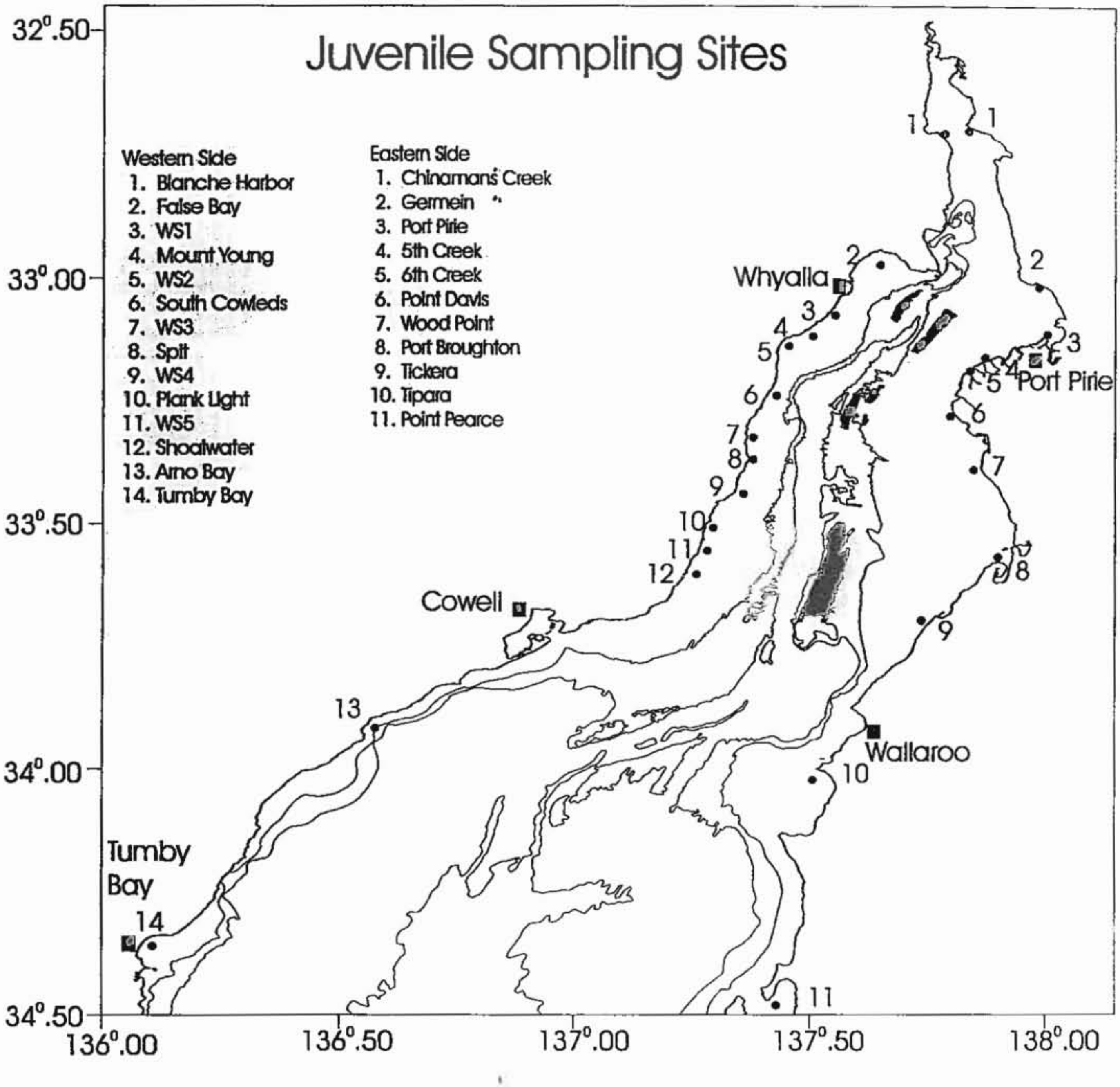


Figure 35: Post larval and juvenile prawn (P. latisulcatus) sampling sites in Spencer Gulf, 1992 - 1994

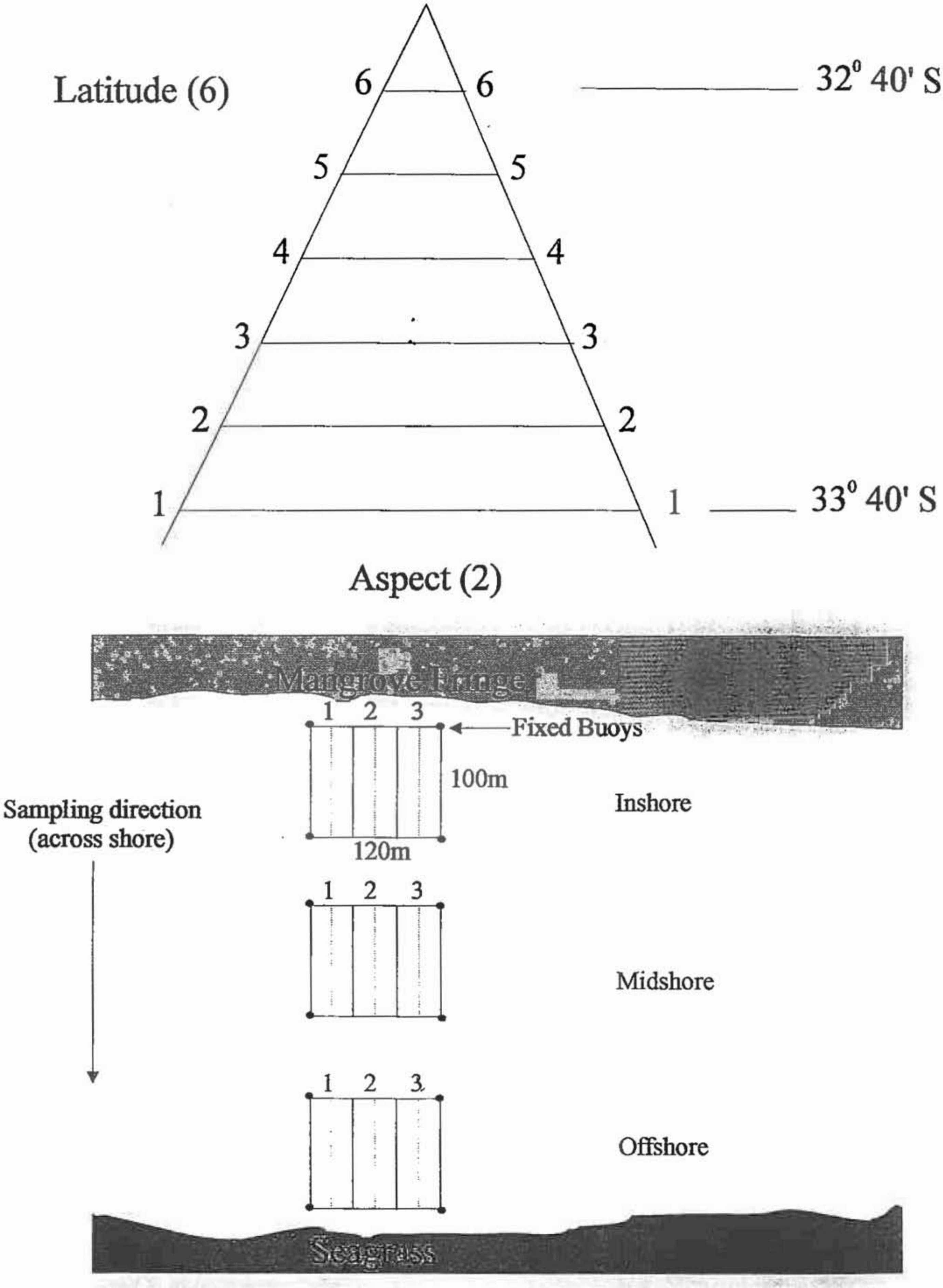


Figure 36: General sampling plan for settlement and juvenile prawn (P. latisulcatus) studies in Spencer Gulf.

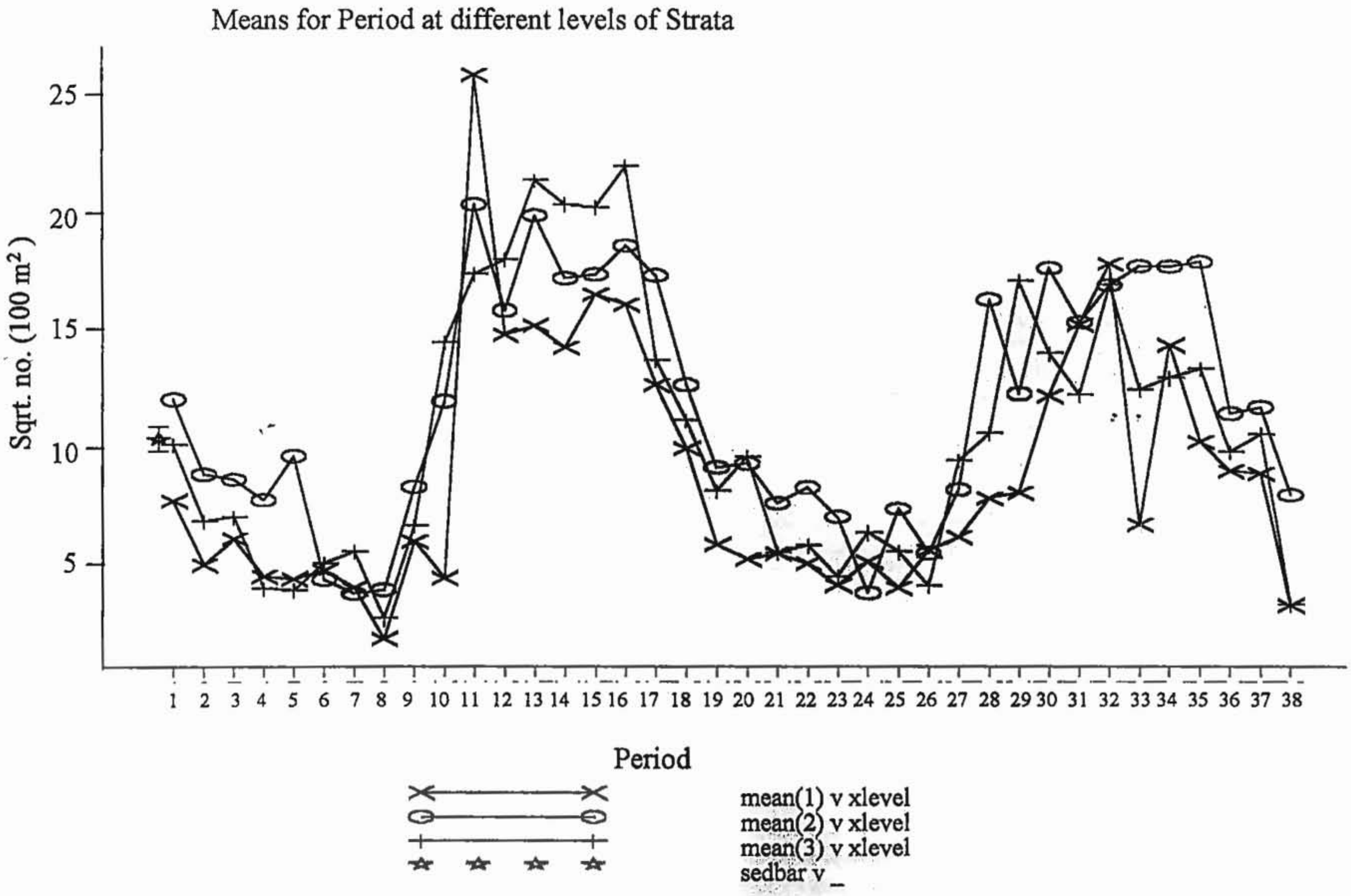


Figure 37a: Numbers of juvenile prawns at False Bay over three Strata (1-Inshore, 2- Midshore, & 3- Offshore) and 38 Periods, 1992 - 1994.

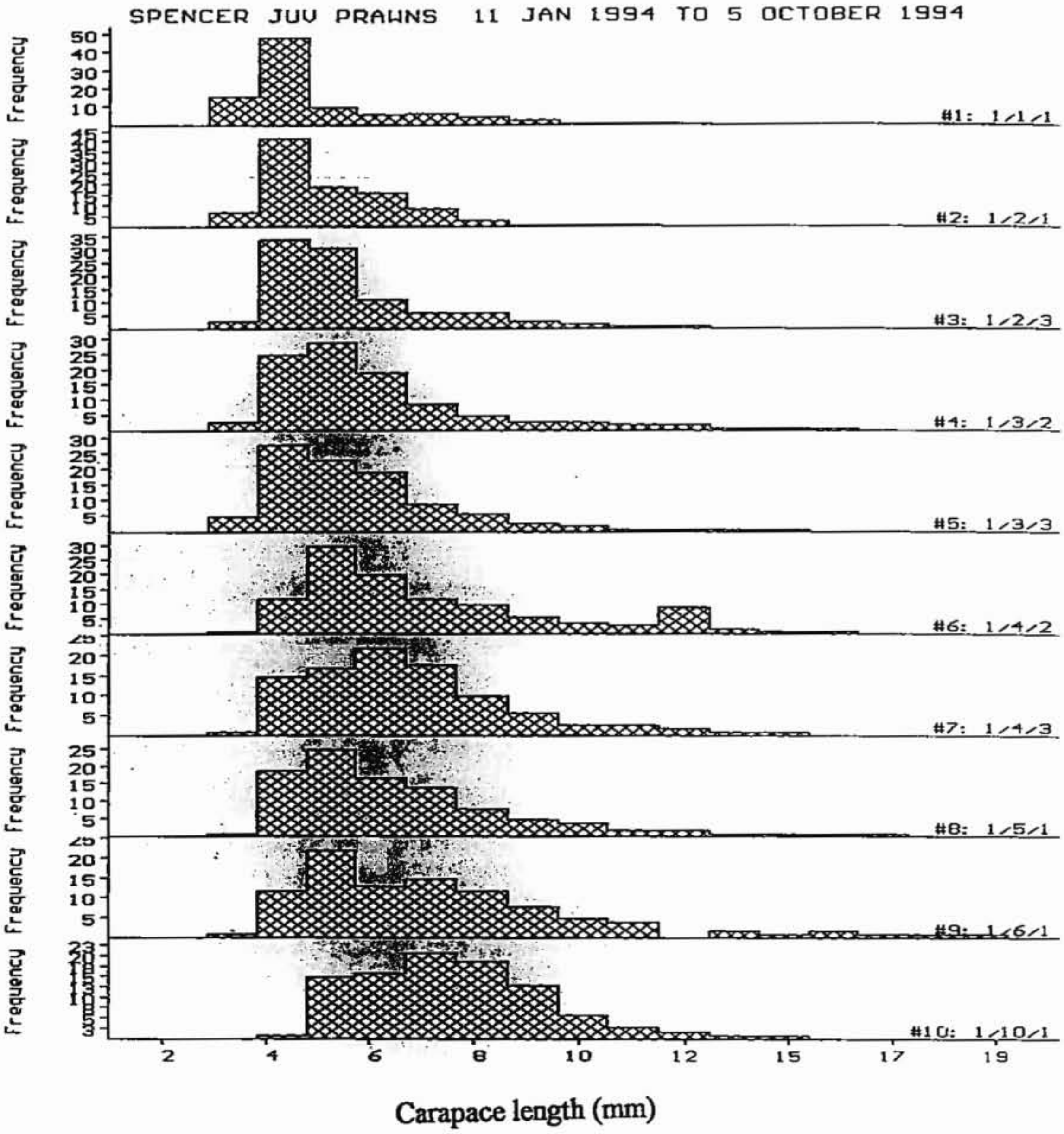


Figure 37b: Multifan plots of juvenile prawn size frequency distributions (%) at False Bay, January - October, 1994.

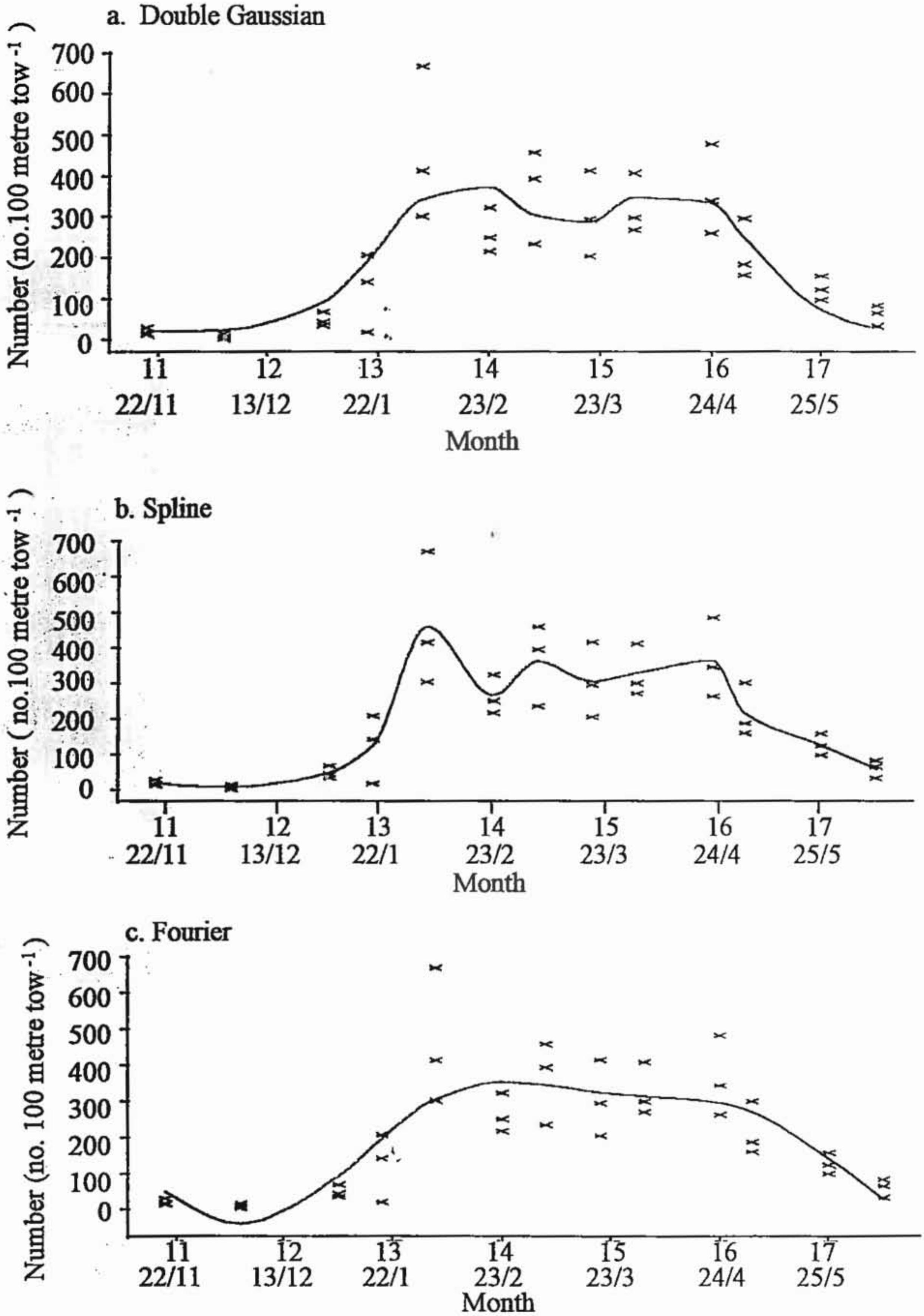


Figure 38: Modelling trends in juvenile P.latisulcatus numbers at False Bay 1992/93.

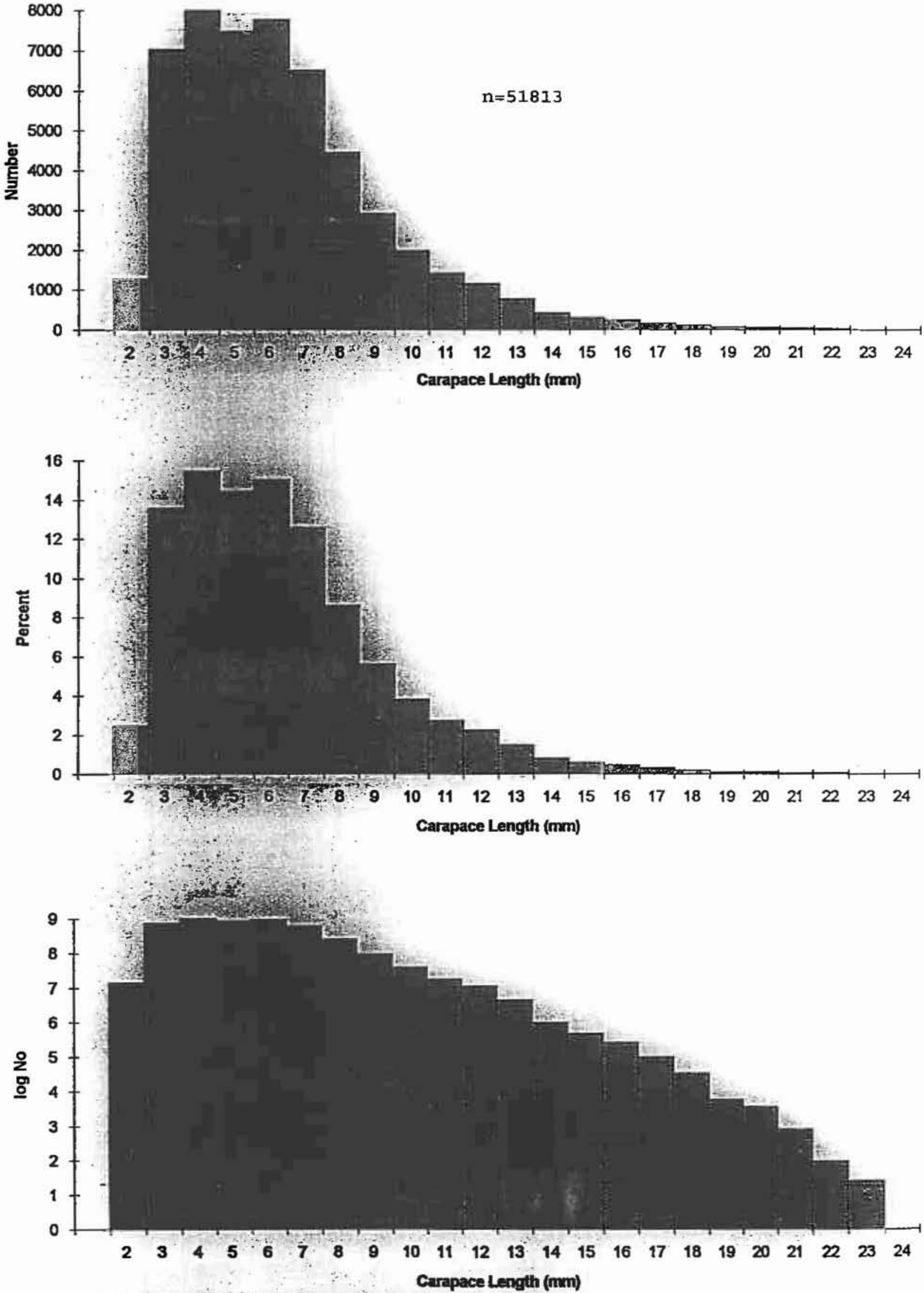


Figure 39: Population structure of benthic post larvae and juvenile P. latisulcatus over 3 strata and 10 sampling sites for 1992 - 94.

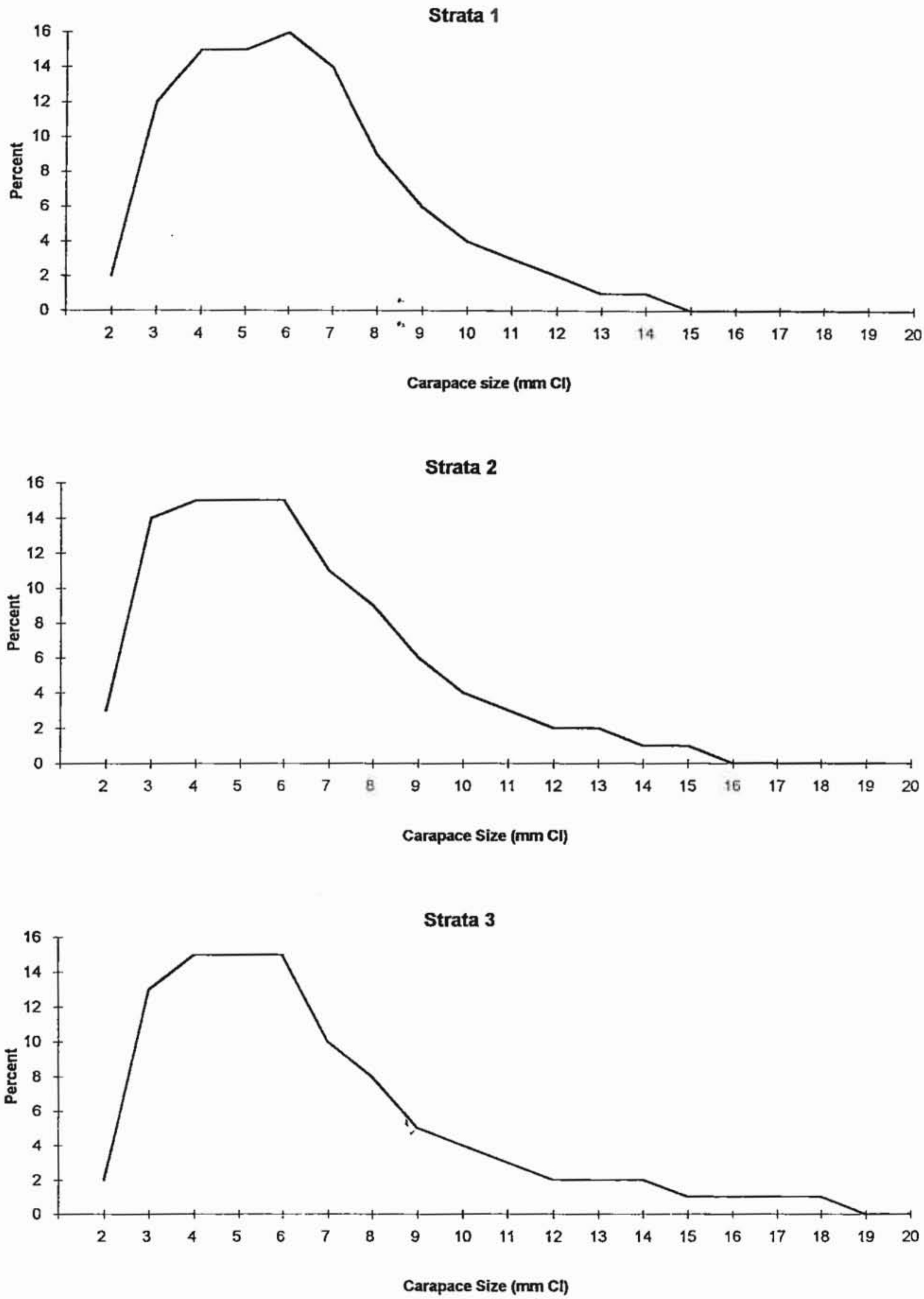
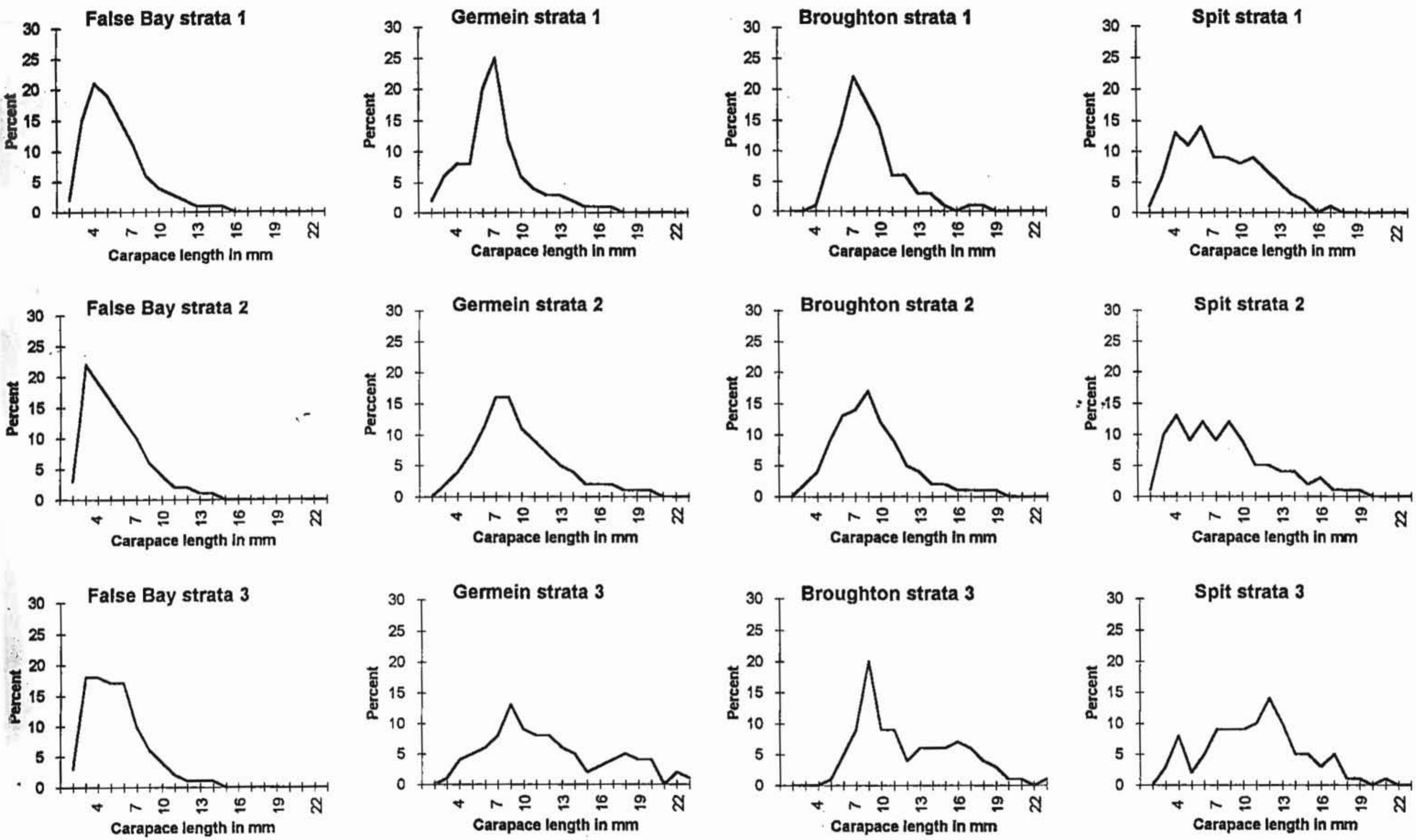


Figure 40: Comparison of the population structure in P. latisulcatus between Strata 1 (inshore, Strata 2 (midshore), and Strata 3 (offshore) over 8 Sites in Spencer Gulf, 1992/93 and 1993/94.



igure 41: Comparison of P. latisulcatus population structure and size over 3 Strata (inshore, midshore and offshore) at False Bay, Germein, Broughton and the Spit, 1993 and 1993/94.

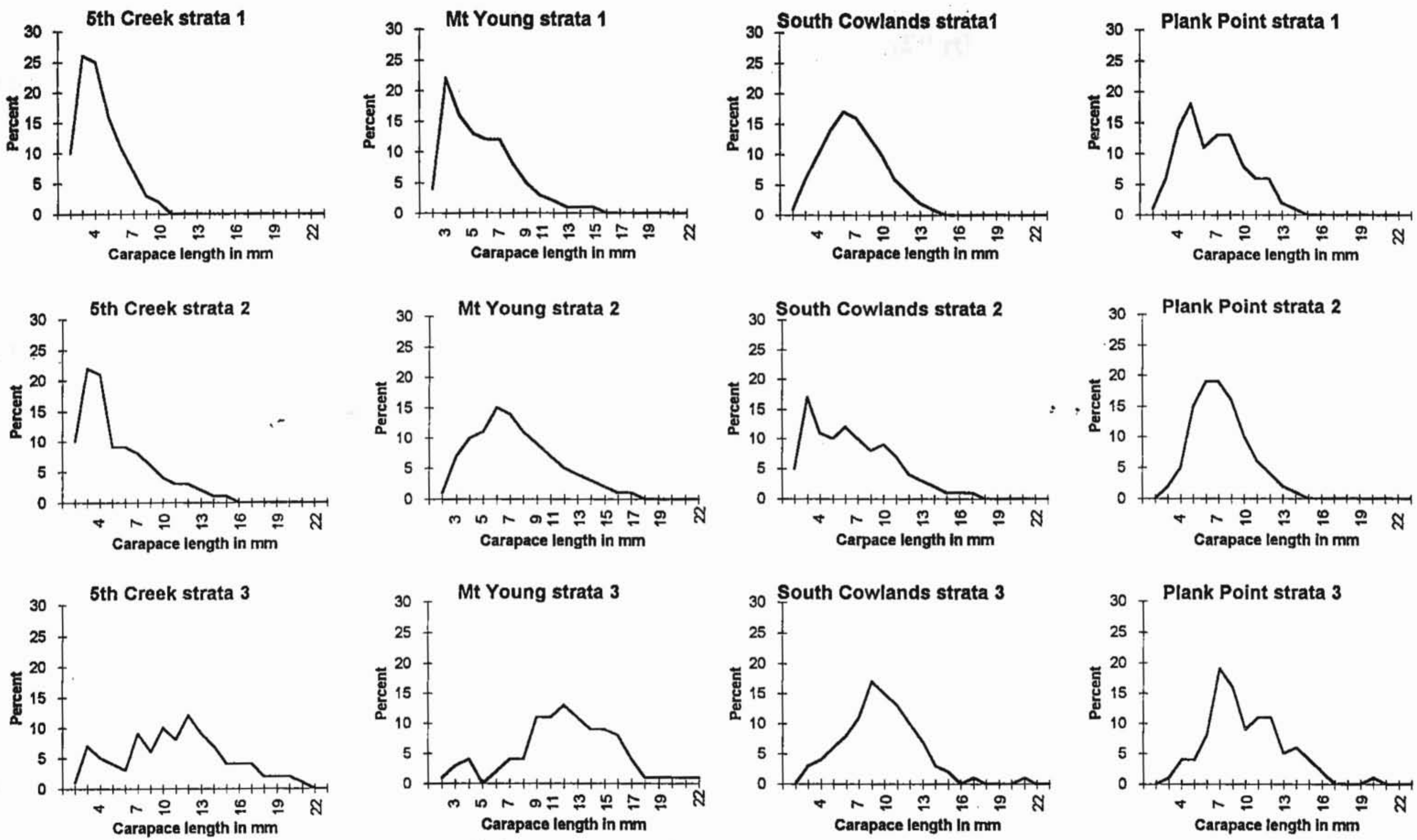


Figure 42: Comparison of P.latisulcatus population structure and size over 3 Strata (inshore, midshore and offshore) at 5th Creek, Mt Young, South Cowlands and Plank Pt over 1992/93 and 1993/94.

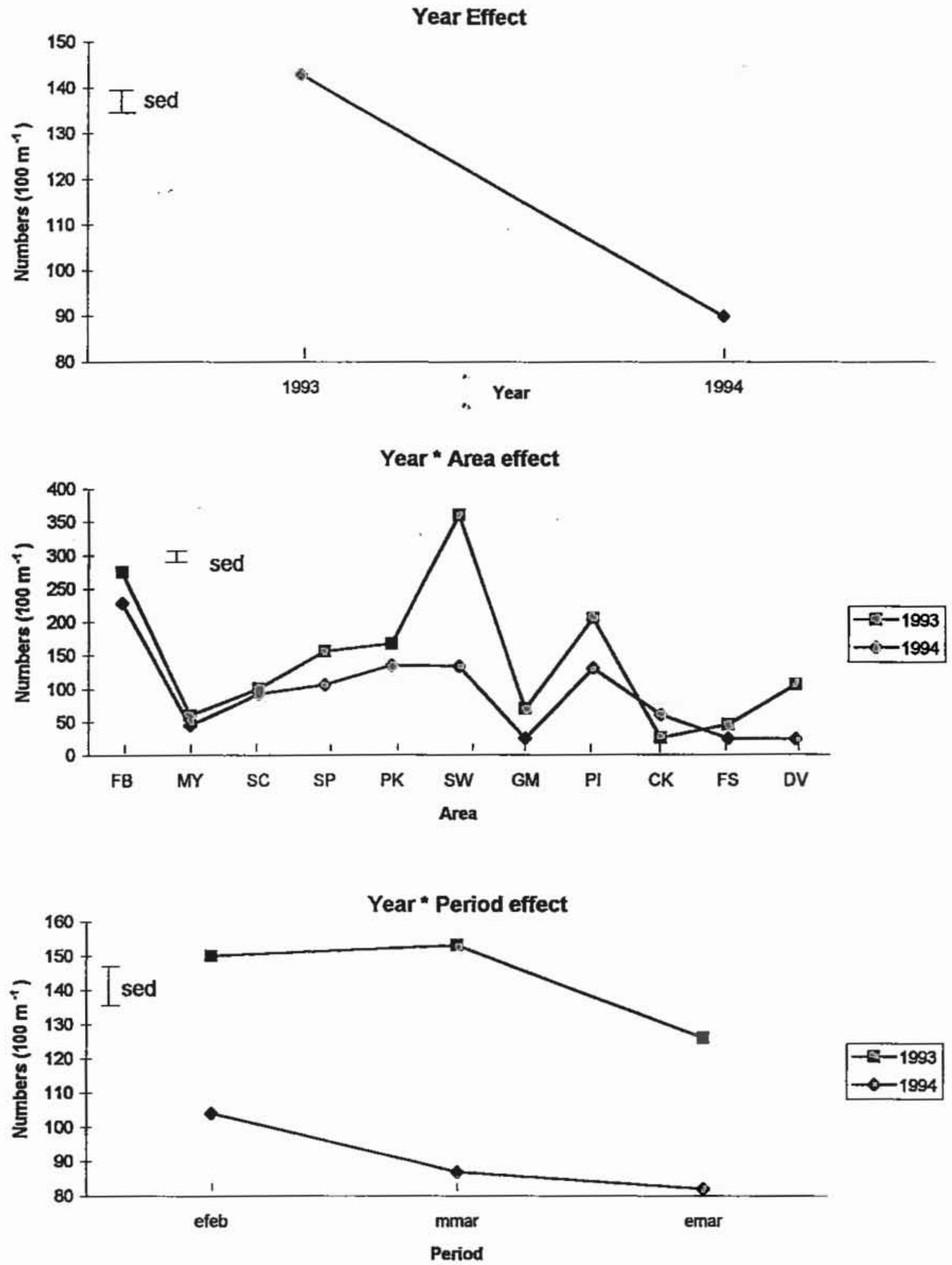
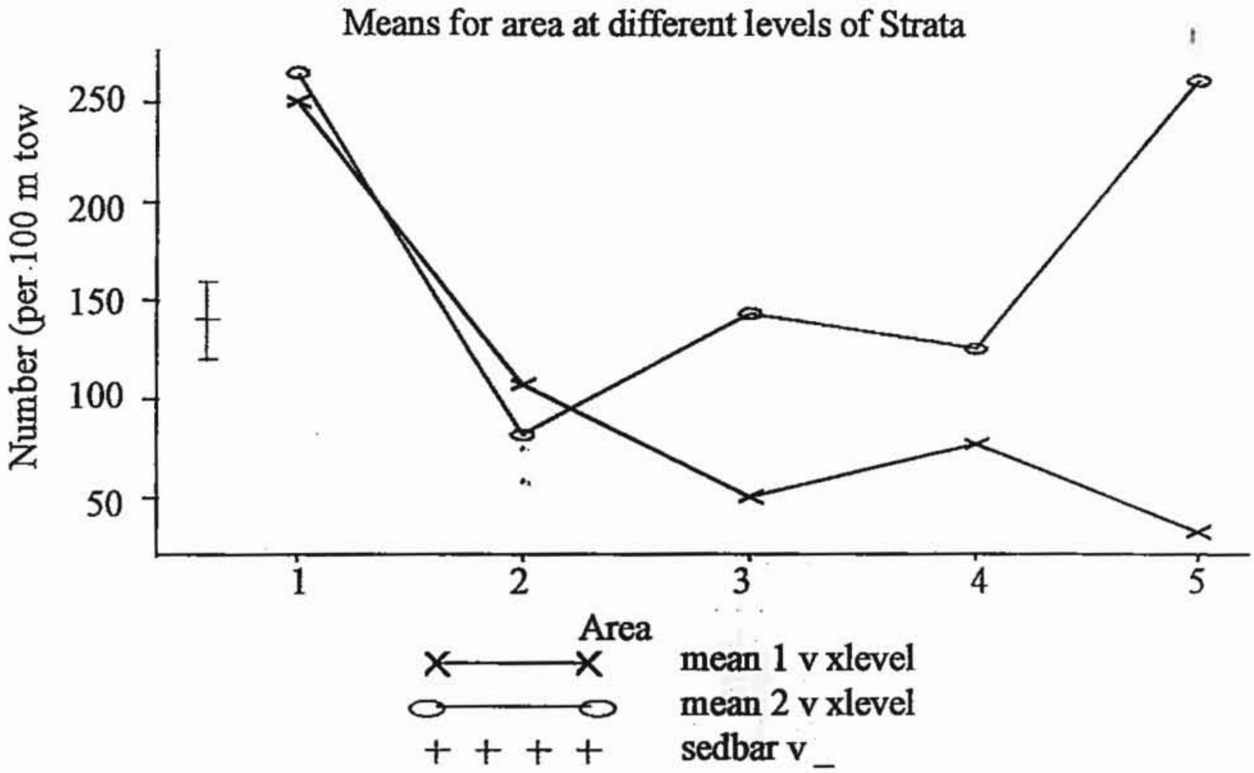


Figure 43: Numbers of P.latisulcatus in inshore nurseries in early February, mid March and late March in 1993 and 1994 over 11 Sites in Spencer Gulf - False Bay (FB), Mt Young (MY), South Cowlands (SC), Spit (SP), Plank Pt (PK), Shoalwater Pt (SW), Germein (GM), Port Pirie (PI), 5th Creek (FS), Fishermans Bay (FS) and Port Davis (DV).



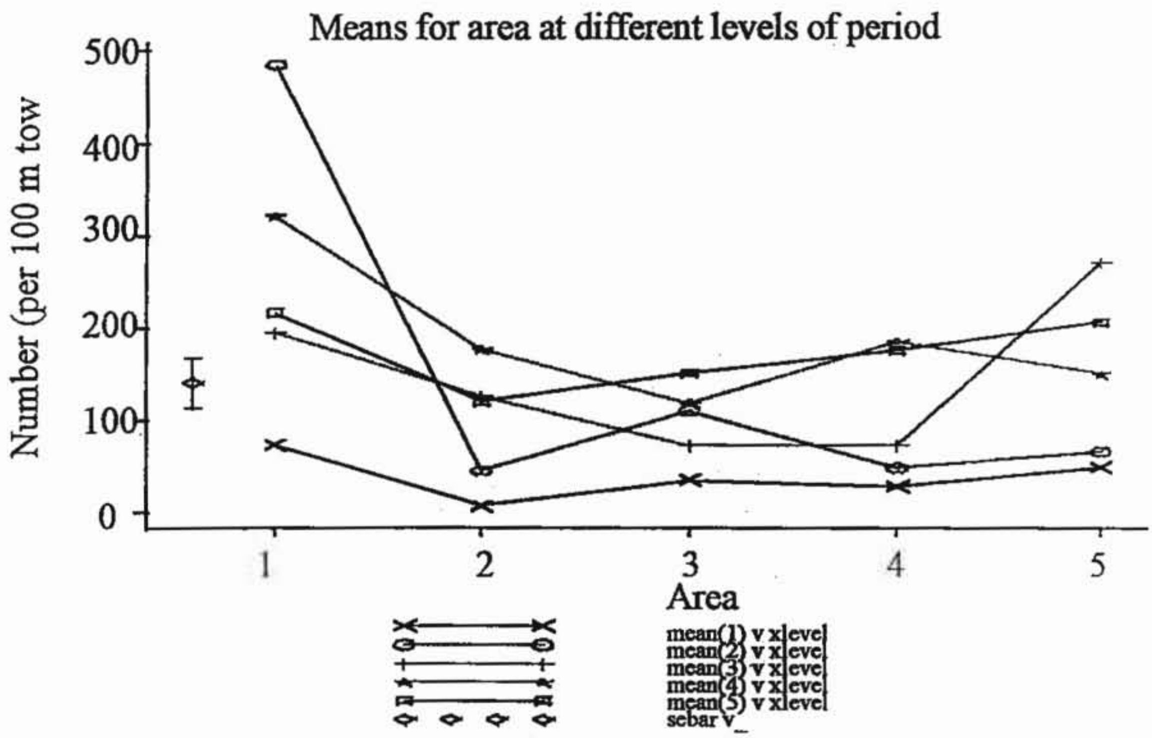


Figure 44: Number of juvenile *P. latisulcatus* over 5 Periods (21/1/93, 7/2/93, 21/2/93, 8/3/93, and 23/3/93) for False Bay (Area 1), South Cowlands (Area 2), Spit (Area 3), Plank Pt (Area 4) and Shoalwater Pt (Area 5).

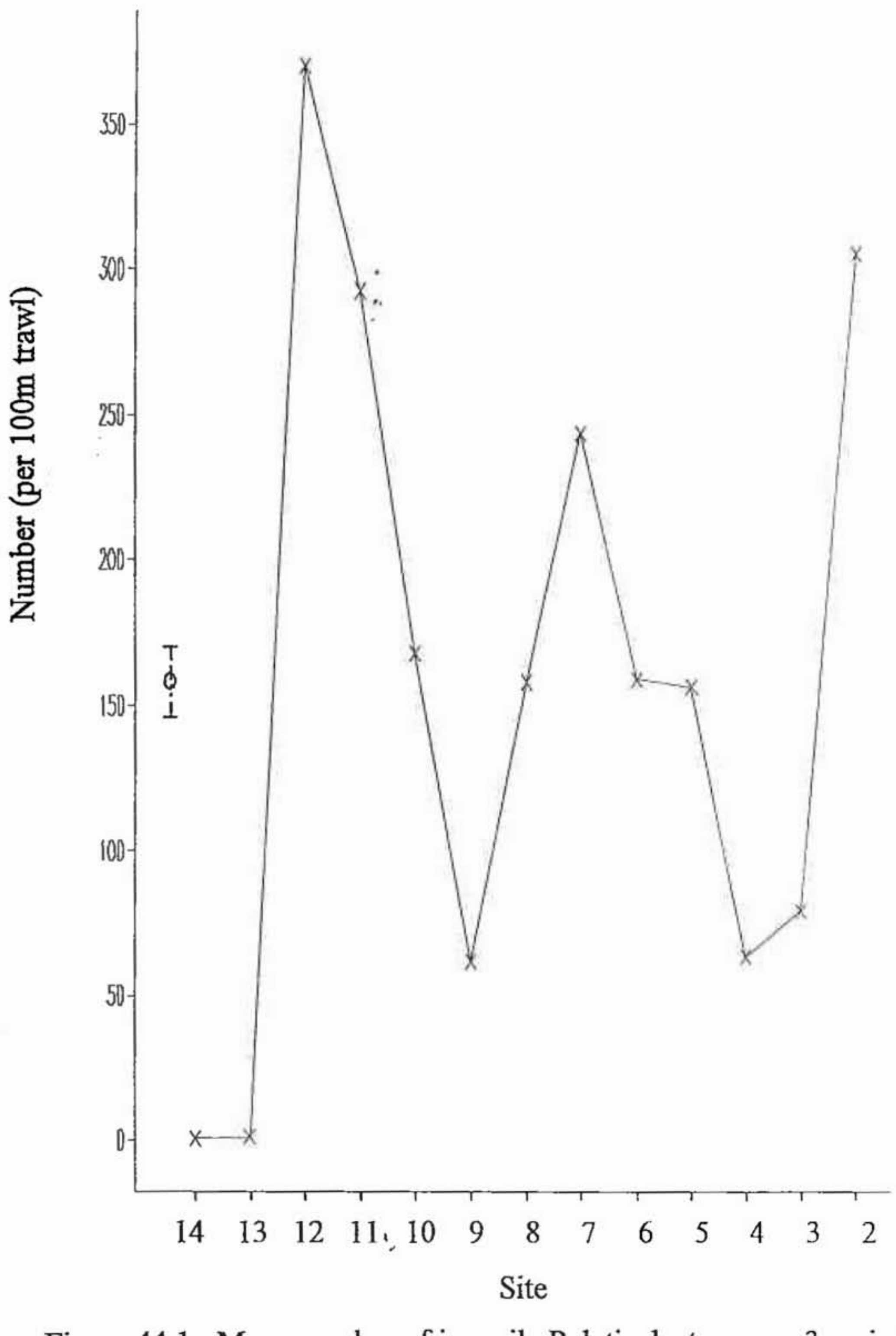


Figure 44.1: Mean number of juvenile <u>P. latisulcatus</u> over 3 periods (February - March) in mid Strata zone from Tumby Bay (34.40° S) to False Bay (33.00° S), 1993

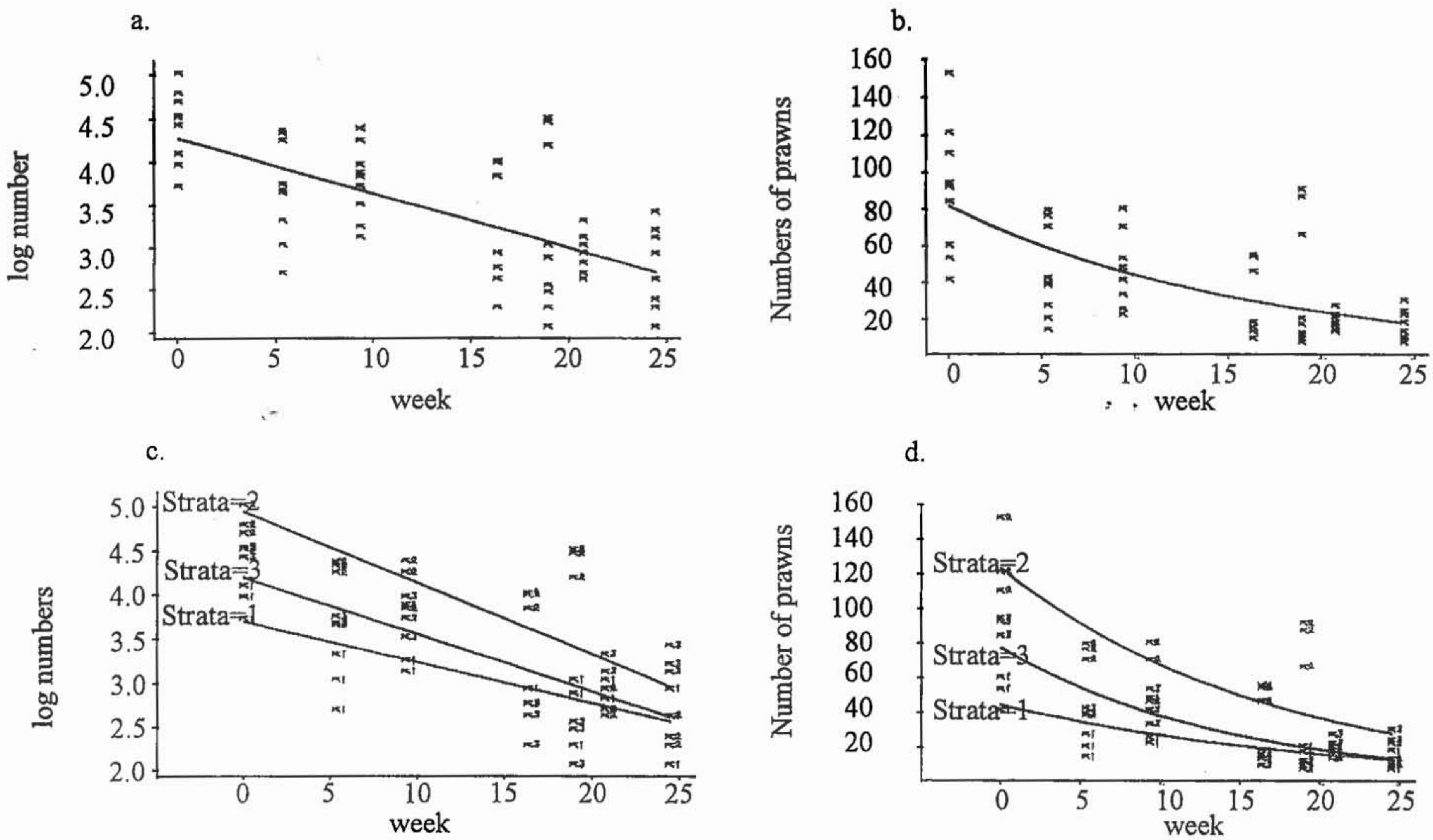


Figure 45: Weekly estimates of <u>P.latisulcatus</u> mortality at False Bay, 1992. a- pooled Strata (linear fit); b- pooled Strata (GLM Poisson Link fit); c- separate Strata (linear fit) and d- separate Strata (GLM Poisson Link fit).

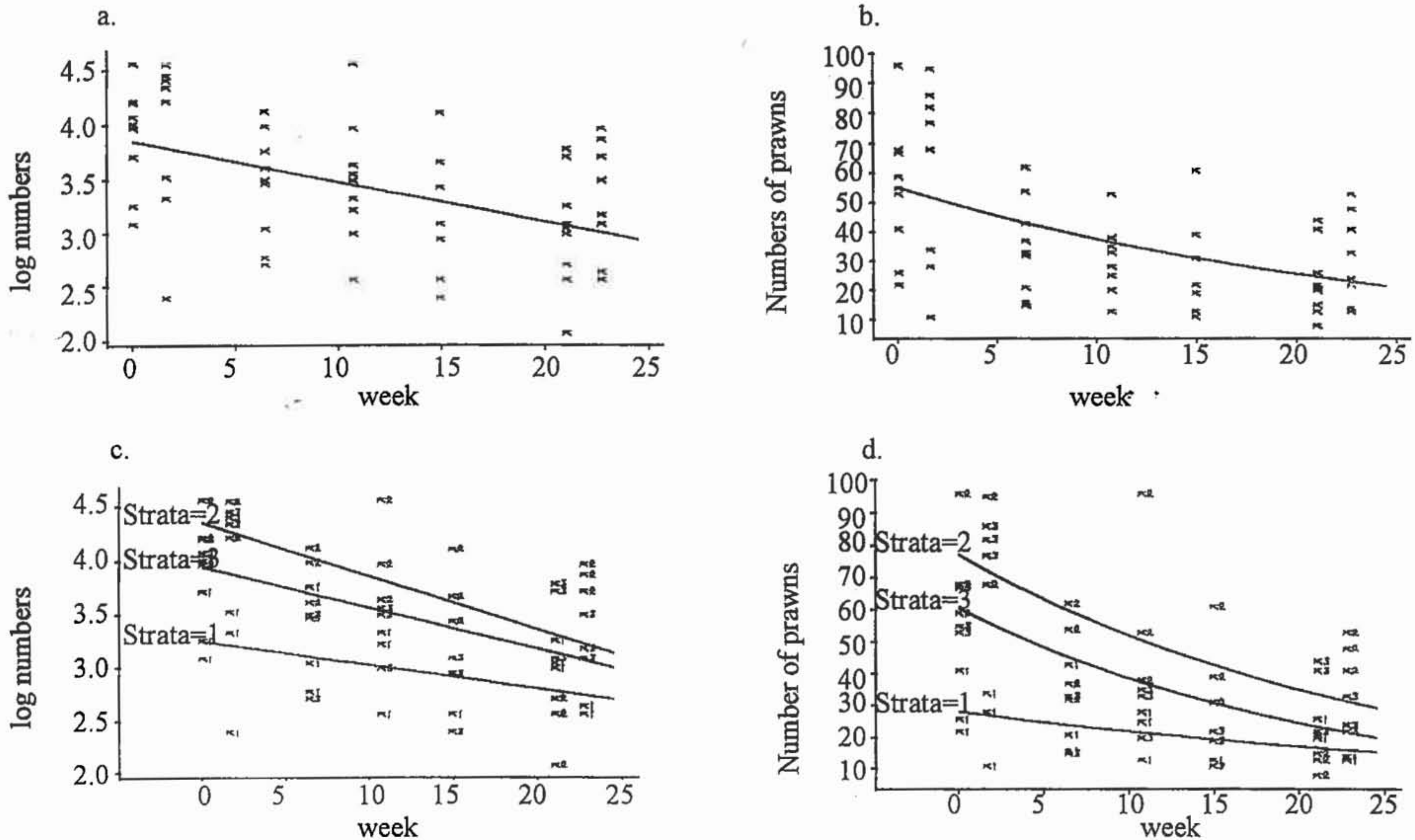


Figure 46: Weekly estimates of P.latisulcatus mortality at False Bay, 1993. a- pooled Strata (linear fit); b- pooled Strata (GLM Poisson Link fit); c- separate Strata (linear fit) and d- separate Strata (GLM Poisson Link fit).

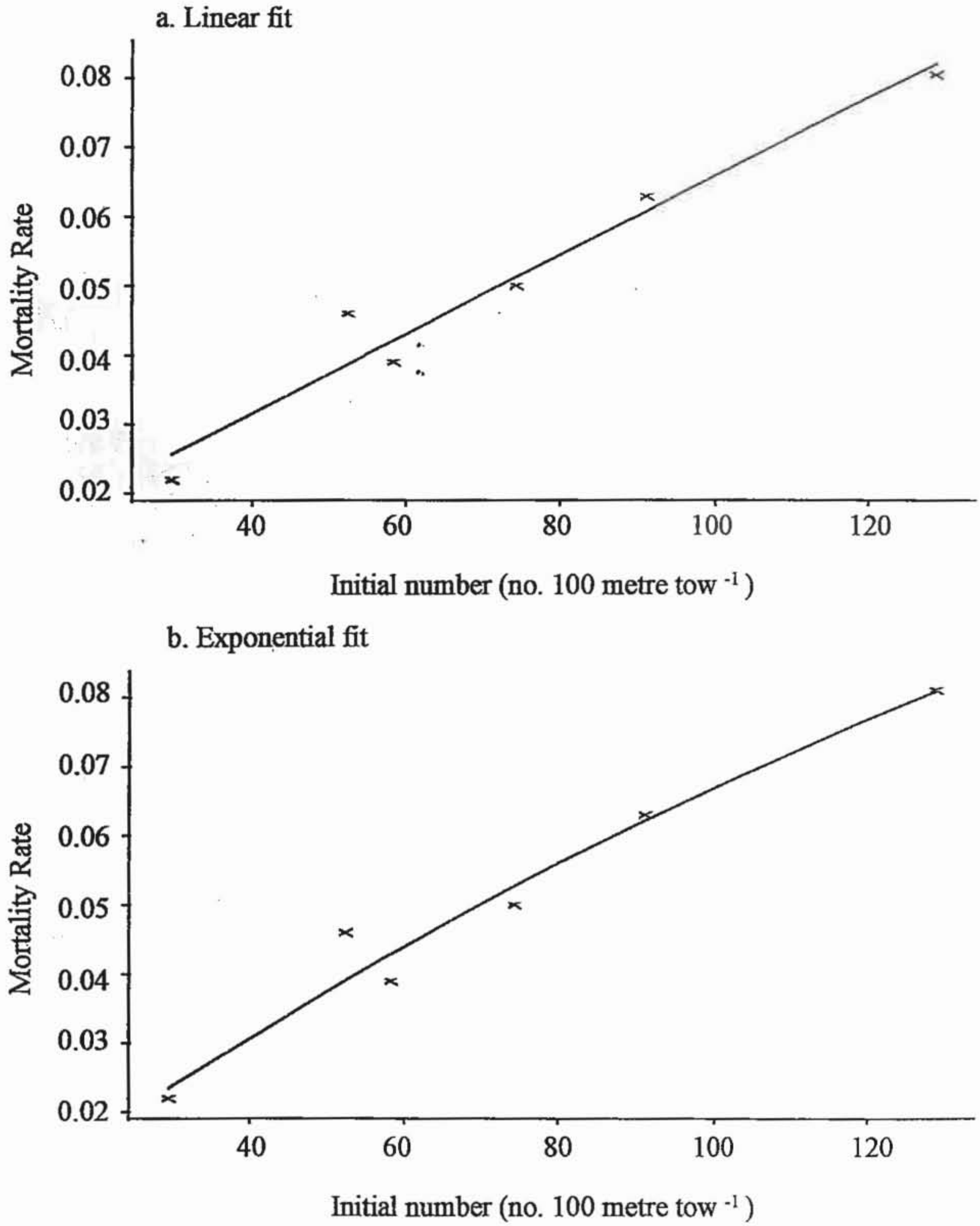


Figure 47: The relationship between initial numbers of juvenile P. latisulcatus and weekly instantaneous mortality at False Bay.

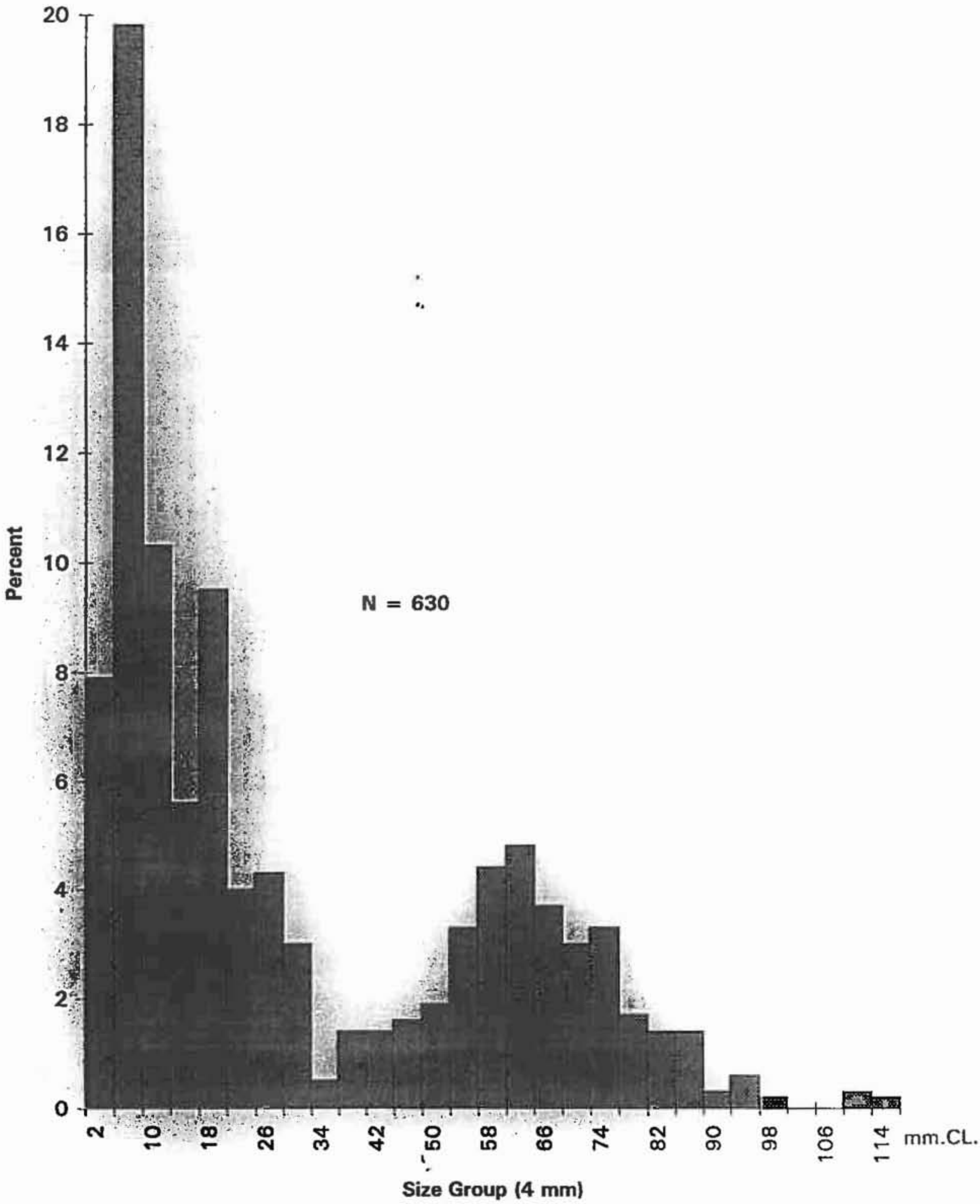


Figure 48: Blue crab (Portunis pelagicus) population structure, western side of Spencer Gulf, January - April 1994

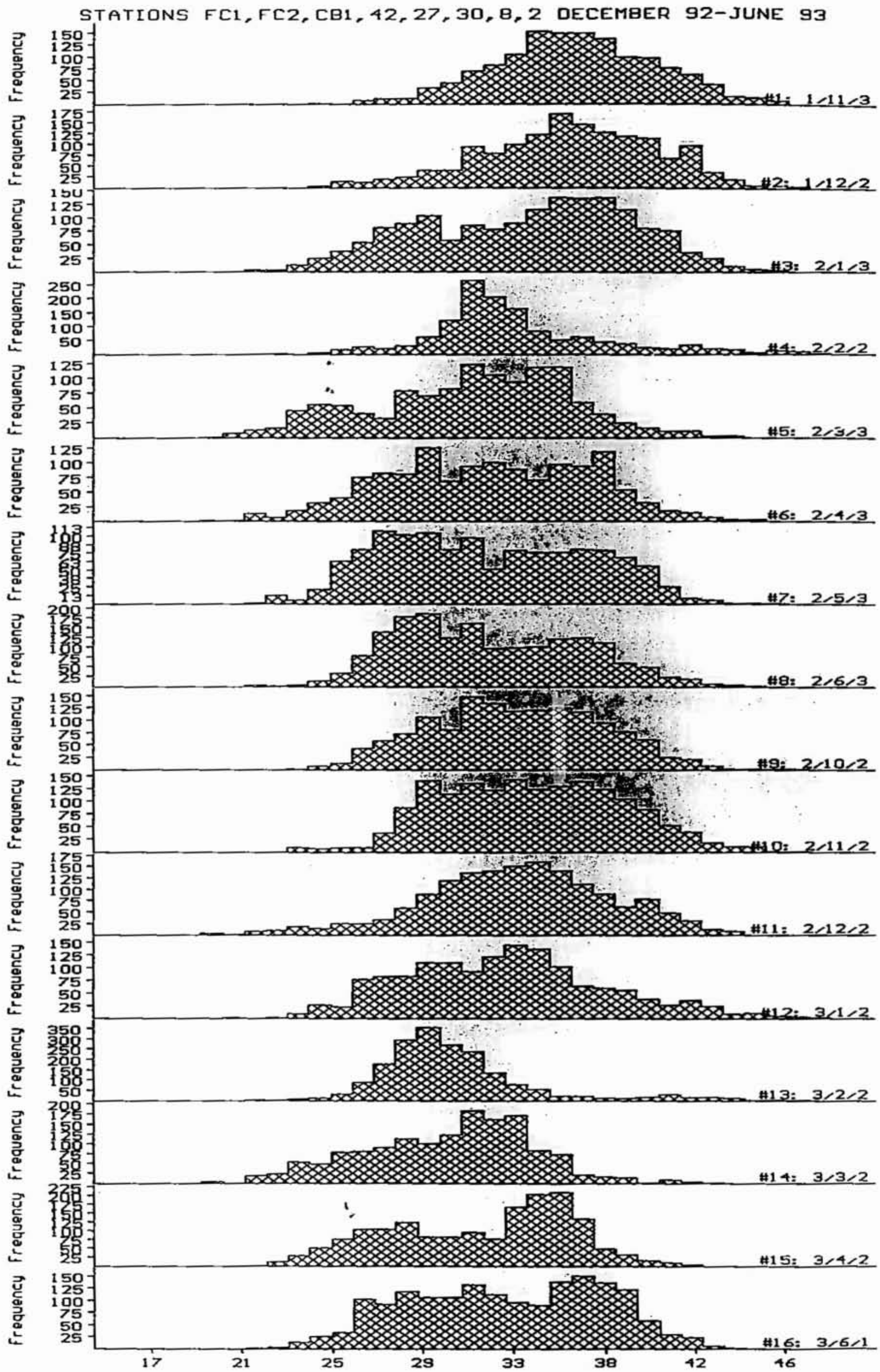


Figure 49: Population structure of P. latisulcatus and recruitment to subnurseries and grounds in Spencer Gulf December 1992 - June 1993.

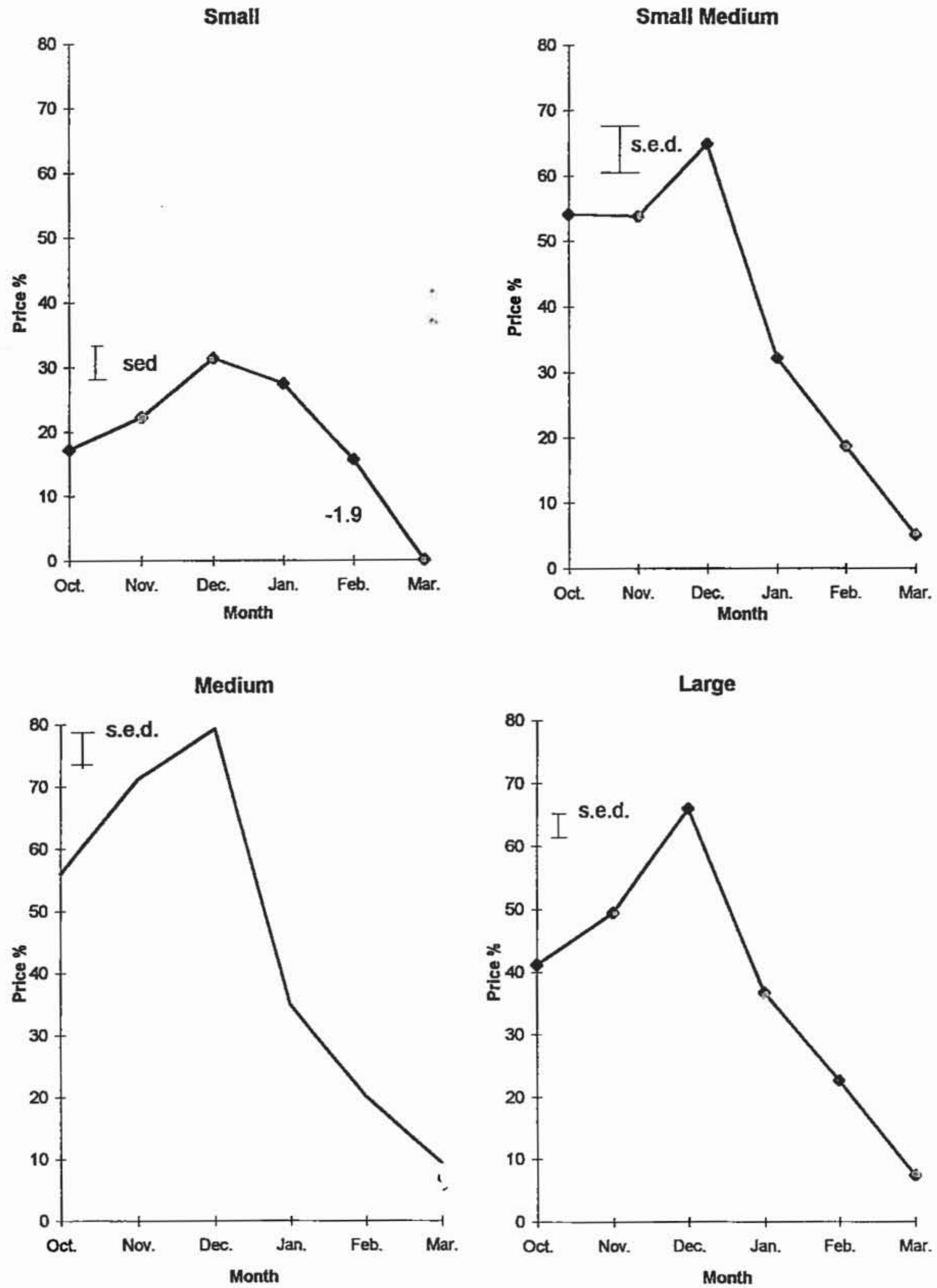


Figure 50: Price premiums for cooked King Prawns on the Sydney Fish Market. Comparison of the % increase in price from May (base) of each year over 1992, 1993 and 1994.

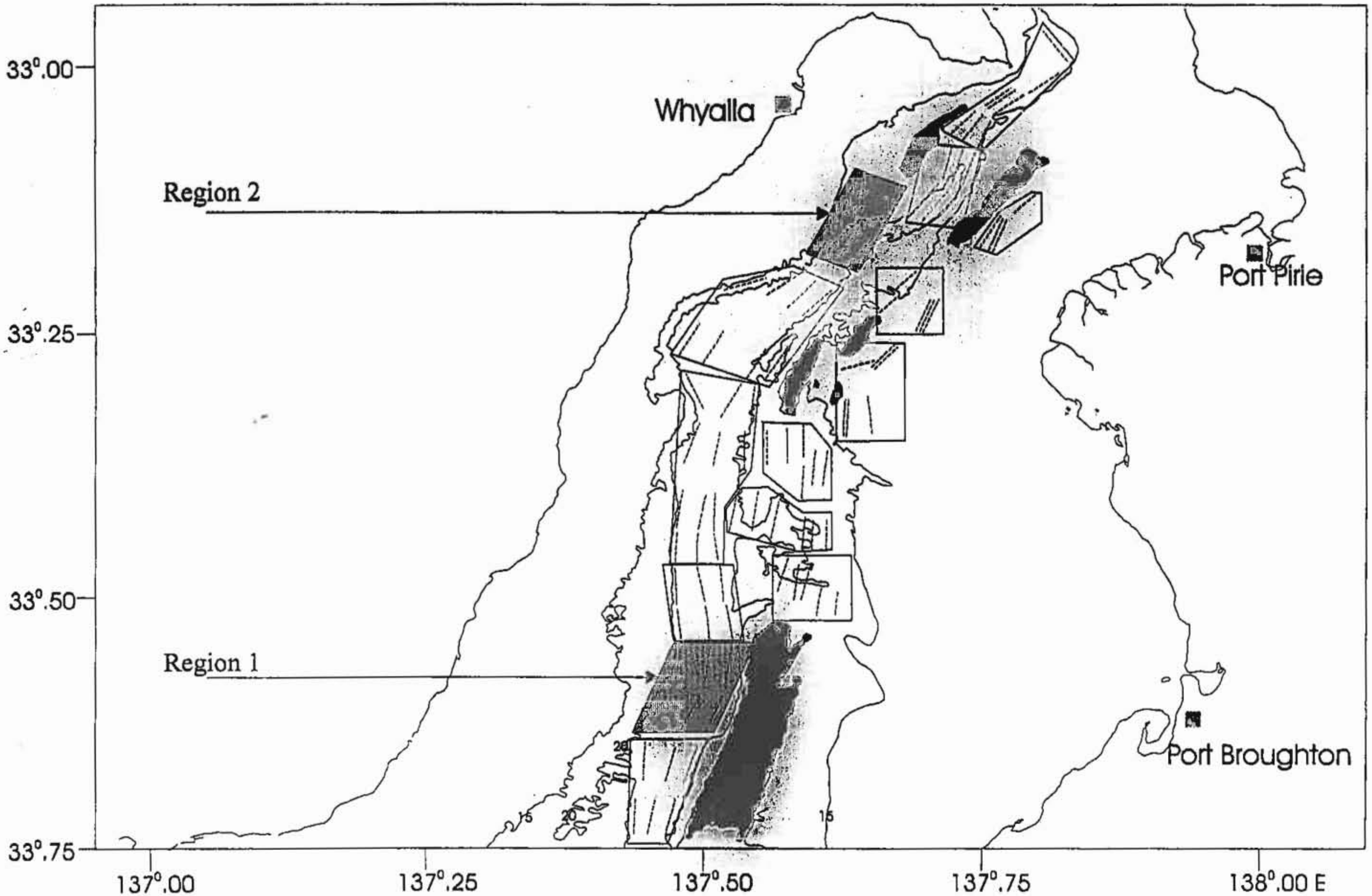


Figure 51 : Schematic diagram showing the location of Region 1 (Middle Bank) and Region 2 (Yarraville Basin).

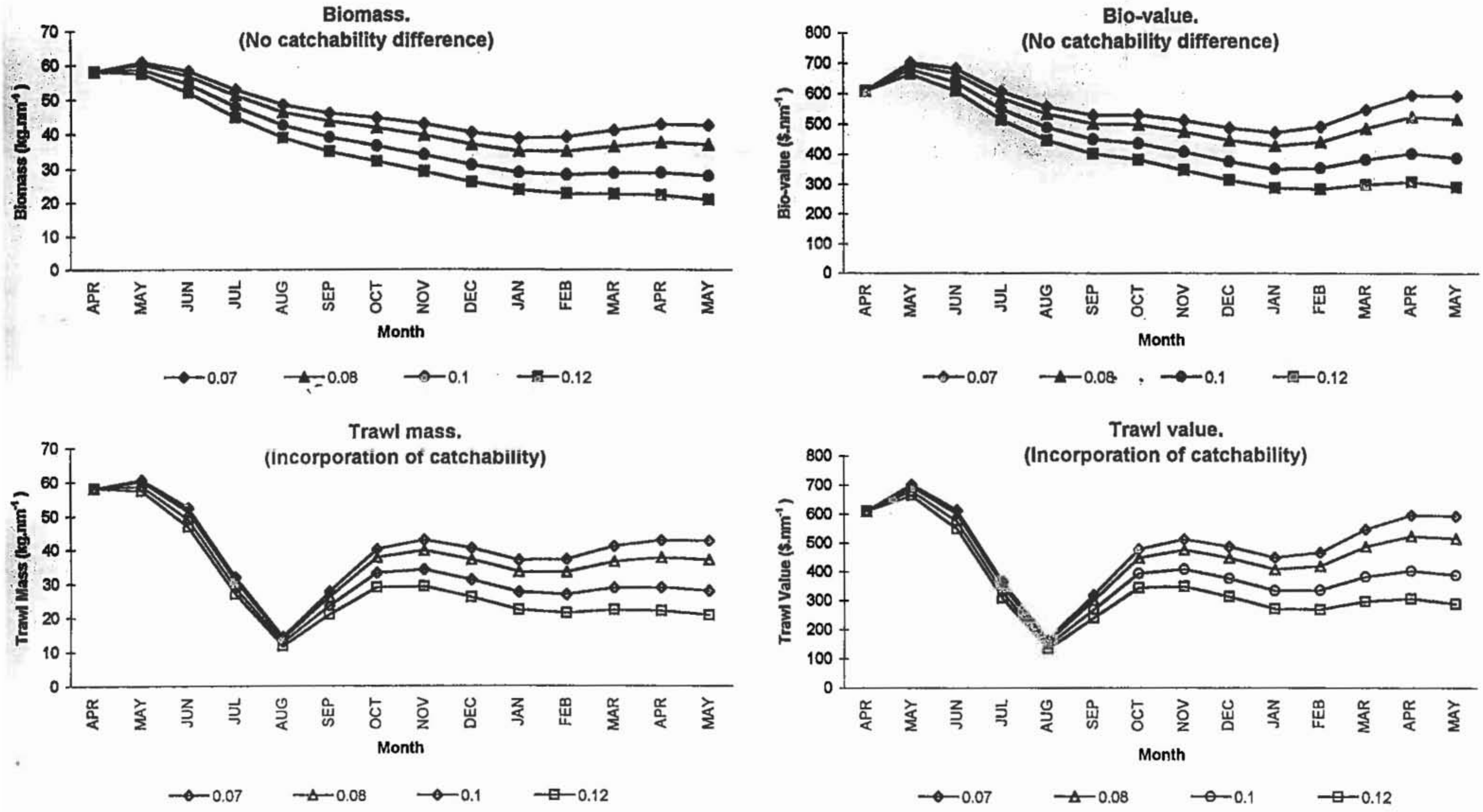
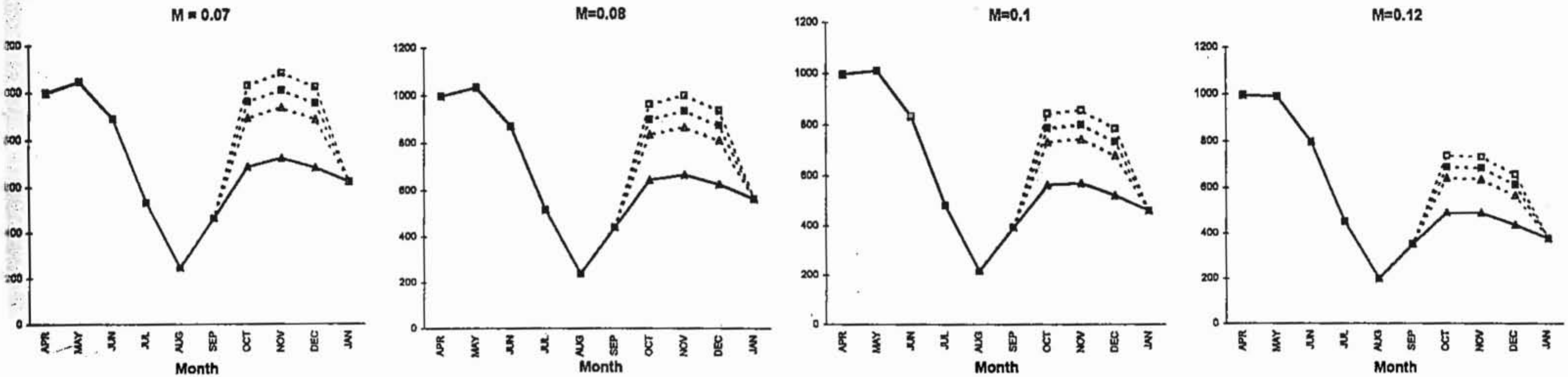


Figure 52: Model simulations of the effect of catchability and Mortality on trawl mass (kg.nm $^{-1}$) and trawl value (\$.nm $^{-1}$).

a) Region 1 - Fished for mid April to May 1988.



b) Region 2 - Fished for November to December 1988.

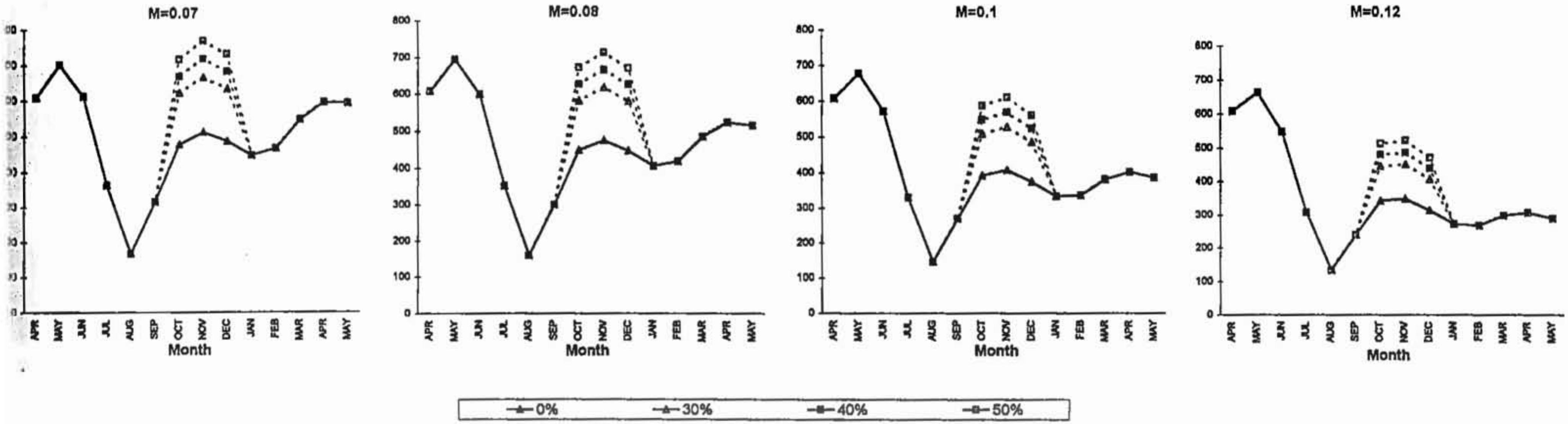


Figure 53: Prawn harvest simulations for Region 1 and Region 2 using a variable price structure with 30, 40 and 50% price premiums in October, November and December in Spencer Gulf.

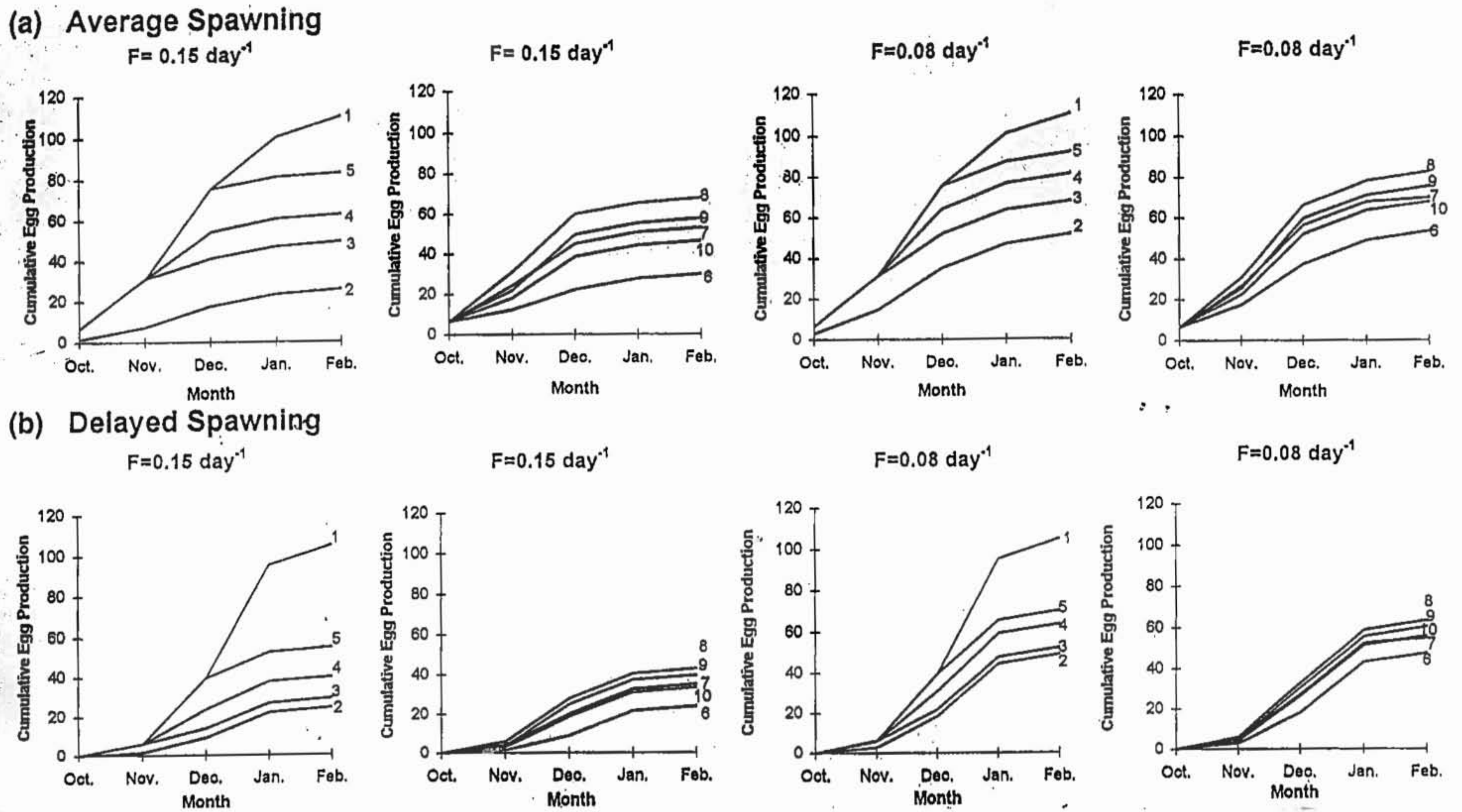


Figure 54: Simulations of the effect of harvesting strategies on cumulative egg production with different fishing mortality rates, exploitation pattern and spawning sequences; - (a) Average spawning; (b) Delayed spawning.

15. TABLES

Table 1: ANOVA of the effects of trawl Board size and Angle of attack on net spread using same gundry design nets.

Source of variation	df	SS	MS	VR	F. pr.
Boardsize	2	20.3475	10.1737	49.80	<0.001
2.74m vs 2.44m	1	2.7075	2.7075	13.25	0.002
2.74m vs 2.13m	1	17.6400	17.6400	86.34	<0.001
Angle	1	0.6338	0.6338	3.10	0.095
Boardsize. Angle	2	2.7975	1.3987	6.85	0.006
2.74m vs 2.44m. Angle	1	2.7075	2.7075	13.25	0.002
2.74m vs 2.13m. Angle	1	0.0900	0.0900	0.44	0.515
Residual	18	3.6775	0.2043		
Total	23	27.4562			

Tables of contrasts

Variate: spread

Boardsize contrasts

2.74m vs 2.44m	0.47	SE	0.130	ss. div.	12.0
2.74m vs 2.13m	1.05	SE	0.113	ss. div.	16.0

Boardsize. Angle contrasts

2.74m vs 2.44m. Angle e.s.e. 0.185 ss. div. 6.0

Angle	1	2
	-0.47	0.47

2.74m vs 2.13m. Angle e.s.e. 0.160 ss. div. 8.0

Angle	1	2
	0.07	-0.07

Tables of means

Variate: spread

Grand mean 15.538

Boardsize	2.74m	2.44m	2.13m
	16.825	15.063	14.725

Angle	1	2
	15.700	15.375

Boardsize Angle	1	2
2.74m	16.825	16.825
2.44m	15.700	14.425
2.13m	14.575	14.875

Table 2: Estimates of P. latisulcatus natural instantaneous mortality (month $^{-1}$) in Spencer Gulf.

Period	Sex	Slope	SE	t	p	F-ratio (time * Sex)
Apr-Nov	Male	-0.099	0.020	-4.95	0.000	
	Female	-0.129	0.028	-4.59	0.000	
	Pooled	-0.114	0.019	-6.06	0.000	0.75
Apr-Nov Drop June	Male	-0.104	0.019	-5.46	0.000	
	Female	-0.132	0.023	-5.79	0.000	
	Pooled	-0.118	0.016	-7.33	0.000	0.78
May-Nov	Male	-0.082	0.024	-2.80	0.006	
	Female	-0.116	0.034	-3.45	0.000	
	Pooled	-0.099	0.021	-4.80	0.000	0.42
May-Nov Drop June	Male	-0.099	0.026	-3.74	0.000	
	Female	-0.128	0.033	-3.88	0.000	
	Pooled	-0.114	0.020	-5.42	0.000	0.50
Jun-Nov	Male	-0.049	0.033	-1.50	0.223	
	Female	-0.092	0.045	-2.06	0.028	
	Pooled	-0.070	0.020	-2.56	0.018	0.60

Table 3: Comparisons of catch rates ($\log_e$ kg.hr^{-1}) in April over 2 years (1988, 1990) during intensive fishing operations at middlebank.

(a). Regression coefficients - 1988 versus 1990.

	Estimate	SE	t
Constant	5.2752	0.0365	144.53
Year, 1990 (difference)	-0.2396	0.0640	-3.75
Day.Year, 1988.	-0.2546	0.0149	-17.09
Day.Year, 1990.	-0.3239	0.0214	-15.10

(b). Test of differences between regression slopes.

Change	df	SS	MS	VR
+ Day	1	33.03041	33.03041	512.97
+ Year	1	6.74745	6.74745	104.79
+ Day.Year	1	0.45276	0.45276	7.03
Residual	211	13.58634	0.06439	
Total	214	53.81696	0.25148	

Table 4: Comparison of survey biomass (kg.nm.$^{-1}$), variance and variance/ mean ratio estimates between intensively fished and unfished regions during 1988.

Fdays	Month	Variance	Mean	v/m
0	April	627.9	82.0	7.7
7	May	320.5	26.7	12.0
14	June	5.9	6.2	1.0
0	April	731.4	58.3	12.6
0	May	352.6	52.6	6.7
14	June	18.0	11.3	1.6
0	April	477.5	97.5	4.9
0	May	335.1	52.0	6.4
3	June	55.6	26.7	2.1
0	April	633.0	101.7	6.2
0	May	330.0	67.4	4.9
3	June	48.9	32.7	1.5
0	April	657.9	105.9	6.2
0	May	999.4	92.3	10.8
0	June	507.6	96.0	5.3
0	April	286.4	86.8	3.3
0	May	729.4	87.4	8.3
0	June	1268.3	74.0	17.1
0	April	802.8	58.3	13.8
0	May	488.1	52.3	9.3
0	June	314.9	57.4	5.5

Table 5: Multiple regression of spawners and temperature on recruits in Spencer Gulf.

(a) Spawner - recruits

	df	MS	F-ratio		Estimate	SE	t-value
Regressio	1	1.40E+07	22.6	Constant	163	418	0.39
Residual	8	60896		Spawner	21.71	4.57	4.75
Total	9	207021					
Percent variance		70.60%					

(b) Recruit - Spawners + Temp 1

	df	MS	F-ratio		Estimate	SE	t-value
Regressio	2	790878	19.67	Constant	-5060	2334	-2.17
Residual	8	40204		Spawner	19.57	3.83	5.11
Total	9	207021		Temp1	278	127	2.26
Change	-1	205738	5.12				
Percent variance		80.60%					

(c) Recruit - Spawners + Temp 1 +Temp 2

	df	MS	F-ratio		Estimate	SE	t-value
Regressio	3	587014	34.48	Constant	-3553	1588	-2.24
Residual	8	17024		Spawner	22.99	2.71	8.5
Total	9	207021		Temp 1	683	147	4.64
				Temp 2	-441	136	-3.25
Change	-1	179285	10.53				
Percent variance		91.80%					

(d) Recruits, Spawners, Temp 1,Temp 2, Temp 3

	df	MS	F-ratio		Estimate	SE	t-value
Regressio	4	453152	44.8	Constant	-3999	1240	-3.22
Residual	5	10116		Spawner	25.04	2.27	11.01
Total	9	207021		Temp 1	1033	182	5.52
				Temp 2	-183	155	-1.19
				Temp 3	-562	249	-2.26
Change	-1	51568	5.1				
Percent variance		95.10%					

Table 6: A-F test of gaussian versus dgaussian fit to maturity data from 3 Regions in Spencer Gulf where Region 1-stn 42, 27; Region 2-stn 22,21, Region 3-stn2, Wal 8

A. F tests of residual sums of squares

a. region 1: dgaussian means- M=1.48 ± 0.05, N=2.94 ± 0.08; gaussian mean M=2.13 ± 0.08 month

	RSS	df	RMS	RSS diff/dfd	F(2,6)	p	%V
dgaussian	60.93	6	10.15	109.7	10.81	<0.05	98.2
gaussian	280.30	8					93.9
total	6280.00	11					

a. region 2: dgaussian means-M=1.50 ± 0.07, N=3.35 ± 0.09; gaussian mean M=2.42 ± 0.16 month

	RSS	df	RMS	RSS diff/dfd	F(2,6)	p	%V
dgaussian	142.5	6	23.75	259.65	10.93	<0.01	92.9
gaussian	661.8						75.2
total	3670.7	11					

a. region 3: dgaussian means-M=1.60 ± 0.06, N=3.47 ± 0.09; gaussian mean M=2.38 ± 0.13 month

	RSS	df	RMS	RSS diff/dfd	F(2,6)	p	%V
dgaussian	130.5	6	21.75	221.8	10.20	<0.05	94.9
gaussian	574.1	8					83.3
total	4737.7	11					

Table 7: **Estimates of mean larval mortality, <u>Penaeaus latisulcatus</u>**

Stage	Rate (No. 100 m $^{-3}$)	Duration (days)	Modified count	Interval (days)	Mortality per day
Zoea	190.85	6	31.800		
				7.5	0.266
Mysis	2.92	9	0.324		
				12.0	0.062
Post larval	0.87	10	0.580		

Table 8: ANOVA of juvenile prawn numbers at False Bay over 39 sampling periods from October 1992 to October 1994. Numbers are square root transformed.

Variate: sqrHMS

Source of variation	df (mv)	SS	MS	VR	F pr.
Substrat stratum	2	8.654	4.327	2.6	
Substrat. * Units * stratum					
Period	36 (1)	8372.541	232.571	139.96	< 0.001
Lin	1	223.062	223.062	134.24	< 0.001
Quad	1	298.242	298.242	179.48	< 0.001
Cub	1	348.113	348.113	209.49	< 0.001
Deviations	33 (1)	7503.125	227.367	136.83	< 0.001
Strata	2	518.095	259.047	155.89	< 0.001
Period. Strata	72 (2)	1002.216	13.920	8.38	< 0.001
Lin. Strata	2	26.168	13.084	7.87	< 0.001
Quad. Strata	2	63.083	31.541	18.98	< 0.001
Cub. Strata	2	10.985	5.492	3.31	0.039
Deviations	66 (2)	901.980	13.666	8.22	< 0.001
Residual	220 (6)	365.576	1.662		
Total	332 (9)	10254.854			

Variate: sqrHMS

Grand mean 10.356

Period		Period		Period		Period		Period	
1	9.941	10	10.235	19	7.679	28	11.539	37	10.356
2	6.866	11	21.169	20	8.031	29	12.432	38	4.827
3	7.217	12	16.159	21	6.161	30	14.559		
4	5.390	13	18.782	22	6.342	31	14.205		
5	5.953	14	17.237	23	5.187	32	17.188		
6	4.689	15	18.002	24	5.061	33	12.246		
7	4.408	16	18.855	25	5.604	34	14.950		
8	2.798	17	14.513	26	5.026	35	13.794		
9	6.942	18	11.221	27	7.897	36	10.048		

Strata	1	2	3
	8.752	11.744	10.571

Standard errors of differences of means

Table	Period	Strata	Period Strata
rep.	9	114	3
s.e.d.	0.6077	0.1707	1.0525

Table 9: ANOVA of juvenile prawn numbers over 5 Periods (22/1/93, 7/2/93, 21/2/93, 8/3/93 & 23/3/93) and 2 Strata for 5 geographically separated Sites on the western side of Spencer Gulf; 1 - False Bay, 2 - S. Cowlands, 3 - Spit, 4 - Plank Pt, 5 - Shoalwater Pt.

Source of variation	df	SS	MS	VR	F pr.
Sites	4	582124	145531	70.23	< 0.001
Lin	1	136491	136491	65.86	< 0.001
Quad	1	381910	381910	184.29	< 0.001
Cub	1	46178	46178	22.28	< 0.001
Deviations	1	17545	17545	8.47	< 0.004
Strata	1	197073	197073	95.10	< 0.001
Period	4	422932	105733	51.02	< 0.001
Sites. Strata	4	293534	73384	35.41	< 0.001
Lin. Strata	1	193396	193396	93.32	< 0.001
Quad. Strata	1	42260	42260	20.39	< 0.001
Cub.Strata	1	3441	3441	1.66	< 0.201
Deviations	1	54438	54438	26.27	< 0.001
Sites. Period	16	644189	40262	19.43	< 0.001
Lin. Period	4	355861	88965	42.93	< 0.001
Quad. Period	4	118648	29662	14.31	< 0.001
Cub. Period	4	114733	28683	13.84	< 0.001
Deviations	4	54948	13737	6.63	< 0.001
Strata. Period	4	34439	8610	4.15	< 0.004
Sites, Strata. Period	16	307404	19213	9.27	< 0.001
Lin. Strata. Period	4	106437	26609	12.84	< 0.001
Quad. Strata. Perio	4	134162	33540	16.19	< 0.001
Deviations	8	66805	8351	4.03	< 0.001
Residuals	100	207231	2072		
Total	149	2688925			

Table 10: Estimation of instantaneous mortality of P. latisulcatus, 1992.

Analysis of Variance for Log_e (N)

Source	df	Seq SS	Adj SS	Adj MS	F	p
Strata	2	6.5504	4.4988	2.2494	10.75	0.000
Week	1	17.2645	17.2645	17.2645	82.48	0.000
Strata * week	2	0.8723	0.8723	0.4362	2.08	0.134
Error	57	11.9313	11.9313	0.2093		
Total	62	36.6186				

Term	Coeff	SD	t - value	p
Constant	4.279000	0.111000	38.54	0.000
Week	-0.063565	0.006999	-9.08	0.000
Week * strata				
1	0.017308	0.009898	1.75	0.086
2	-0.017685	0.009898	-1.79	0.079

Analysis of Variance for Log_e (N)

Source	df	Seq SS	Adj SS	Adj MS	F	p
Strata	2	6.5504	4.4988	2.2494	10.75	0.000
Week (strata)	3	18.1368	18.1368	6.0456	28.88	0.000
Error	57	11.9313	11.9313	0.2093		
Total	62	36.6186				

Term	Coeff	SD	t - value	p
Constant	4.27900	0.1110	38.54	0.000
Week				
1	-0.04626	0.01212	-3.82	0.000
2	-0.08125	0.01212	-6.70	0.000
3	-0.06319	0.01212	-5.21	0.000

Table 11: Estimation of instantaneous weekly mortality of P. latisulcatus, 1993.

Source	df	Seq SS	Adj SS	Adj MS	F	p
Strata	2	6.9780	4.7500	2.3750	11.22	0.000
Week	1	5.9247	5.9247	5.9247	27.98	0.000
Strata * week	2	0.5501	0.5501	0.2751	1.30	0.281
Error	57	12.0699	12.0699	0.2118		
Total	62	25.5227				

Term	Coeff	SD	t - value	p
Constant	3.848290	0.096460	39.89	0.000
Week	-0.036930	0.006982	-5.29	0.000
Week * strata				
1	-0.014503	0.009873	1.47	0.147
2	-0.012926	0.009873	-1.31	0.196

Source	df	Seq SS	Adj SS	Adj MS	F	p
Strata	2	6.9780	4.7500	2.375	11.22	0.000
Week (strata)	3	6.9748	6.4748	2.1583	10.19	0.000
Error	57	12.0699	12.0699	0.2118		
Total	62	25.5277				

Term	Coeff	SD	t - value	p
Constant	3.84829	0.09646	39.89	0.000
Week				
1	-0.02243	0.01209	-1.85	0.069
2	-0.04986	0.01209	-4.12	0.000
3	-0.03851	0.01209	-3.18	0.002

Table 12: Estimates of juvenile instantaneous weekly mortality using a GLM Poisson Link function- (a) Separate years; (b) Combined Years.

(a)

M	SE	t	
-0.0616	0.024	-25.48	1992
-0.0387	0.026	-14.92	1993

(b)

M	SE	t	
-0.049	0.002	-28.09	1992 + 93

Table 13: The relationship between initial number of juvenile prawns and weekly instantaneous mortality, (a) linear; (b) exponential.

(a)

	df	SS	MS	VR
Regression	1	0.00196526	0.00196526	91.87
Residual	4	0.00008557	0.00002139	
Total	5	0.00205083	0.00041017	

Percentage variance accounted for 94.8%
Standard error of observaton is estimated to be 0.00463

Estimates of regression coefficients

	estimate	SE	t (4)
Constant	0.00855	0.00473	1.81
init	0.0005749	0.00006	9.58

(b)

Response variate: mort
Explanatory : init
Fitted Curve : A + B*R**X
Constraints : R < 1

	df	SS	MS	VR
Regression	2	0.00197707	0.00098853	40.20
Residual	3	0.00007377	0.00002459	
Total	5	0.00205083	0.00041017	

Percentage variance accounted for 94.0%
Standard error of observaton is estimated to be 0.00496

Estimates of parameters

	estimate	SE
R	0.99517	0.00677
B	-0.174	0.156
A	0.174	0.168

Table 14: ANOVA for estimation of slopes (weekly instantaneous mortality)

Source	df	Seq SS	Adj SS	Adj MS	F	p
year	1	7.693	13.911	13.911	21.90	0.000
week (year)	2	60.924	60.924	30.462	47.95	0.000
Error	243	154.373	154.373	0.635		
Total	246	222.990				

Term	Coeff	SD	t - value	p
Constant	3.873	0.073	53.03	0.000
Year	0.342	0.073	4.68	0.000
Week	-0.082	0.009	-9.14	0.000
Week * year	-0.030	0.008	-3.53	0.001

Table 15: Comparison of juvenile prawn weekly mortality rates.

(a) Literature

		Mortality Rate	% Weekly Mortality
O'Brien (1994)	Minimum	0.06	5.82
O'Brien (1994)	Maximum	0.29	25.17
O'Brien (1994) - September/ August	1988/89	0.15	13.93
	1989/90	0.17	15.63
Minello et. al. (1989) - upper range	89		33.60
Haywood & Staples (1993)	Maximum range		60.90
	1988		26.00
	1989		38.70
	1990		36.90

(b) Spencer Gulf - FRDC Program

		Mortality Rate	% Weekly Mortality
Pooled Year	1992 + 93	0.050	4.88
Pooled Strata	1992	0.064	6.20
	1993	0.037	3.63
Strata within Year 1992	Strata 1	0.046	4.50
	Strata 2	0.081	7.78
	Strata 3	0.063	6.11
Strata within Year 1993	Strata 1	0.022	2.18
	Strata 2	0.050	4.88
	Strata 3	0.039	3.82

16. APPENDICES

The effect of engine horse power, vessel mass, vessel length, gross tonnage and trawl board size on fishing power. Unrestricted analysis of 34 vessels from small to large size (14.3 -25.3 m) with power averaged over 3 years 1987/88-1989/90.

(a) Linear regression of each variate on fishing power.

	V %	Constant	SE	t	Slope	SE	t
sqrtBHP	23.2	0.333	0.160	2.080	0.027	0.009	3.31
mass	1.9	0.809	0.048	16.750	0.001	0.004	1.25
loa	2.5	0.656	0.158	4.290	0.011	0.008	1.36
grt	0.1	0.815	0.050	16.400	0.001	0.001	1.01
bsize	19.4	0.061	0.269	0.230	0.302	0.101	2.99

(b) Multiple linear regression

(i) Without boardsize as a variate

	Estimate	SE	t	V%
constant	0.386	0.216	1.79	19.8
sqrtbhp	0.037	0.013	2.87	
mass	0.001	0.017	-0.74	
grt	-0.001	0.002	-0.78	
loa	-0.013	0.001	0.98	

(ii) With boardsize as a variate

	Estimate	SE	t	V%
constant	-0.480	0.301	-1.59	44.7
sqrtbhp	0.033	0.011	3.05	
mass	-0.004	0.015	-0.26	
grt	-0.002	0.001	-1.51	
loa	0.001	0.001	1.10	
bsize	0.320	0.090	3.57	

(iii) The relationship between fishing power and sqrtbhp, loa and board size

	Estimate	SE	t	V%
constant	-0.317	0.259	-1.22	40.0
sqrtbhp	0.034	0.010	3.42	
loa	-0.011	0.009	-1.27	
bsize	0.283	0.088	3.20	

APPENDIX 2

The relationship between fishing power and engine bhp, vessel length and board size from 1987/88-1989/90

(a) 1987/1988

(i) Without boardsize

	Estimate	SE	t	%V
Constant	0.336	0.217	1.55	12.4
sqrtbhp	0.0337	0.0147	2.29	
loa	-0.0067	0.0125	-0.54	

(ii) With boardsize

	Estimate	SE	t	%V
Constant	-0.512	0.341	-1.5	30.5
sqrtbhp	0.0335	0.0131	2.55	
loa	-0.0111	0.0112	-0.99	
bsize	0.351	0.116	3.01	

(a) 1988/1989

(i) Without boardsize

	Estimate	SE	t	%V
Constant	0.5400	0.1920	2.82	6.9
sqrtbhp	0.0264	0.0130	2.03	
loa	-0.0093	0.0110	-0.84	

(ii) With boardsize

	Estimate	SE	t	%V
Constant	0.0360	0.3250	0.11	14.0
sqrtbhp	0.0263	0.0125	2.10	
loa	-0.0119	0.0107	-1.11	
bsize	0.2090	0.1110	1.88	

(a) 1989/1990

(i) Without boardsize

	Estimate	SE	t	%V
Constant	0.2220	0.2160	1.03	22.5
sqrtbhp	0.0425	0.0147	2.90	
loa	-0.0059	0.0124	-0.47	

(ii) With boardsize

	Estimate	SE	t	%V
Constant	-0.475	0.356	-1.34	32.6
sqrtbhp	0.0423	0.0137	3.09	
loa	-0.0095	0.0117	-0.81	
Bsize	0.289	0.121	2.38	

Appendix 3.1 : The effect of engine power, vessel mass, length, gross tonnage and board size on fishing power -vessels G.E. 300 BHP, G.E. 18.0 metres.

(a) Linear regression

	R^2%	Constant	SE	t	Slope	SE	t
sqrt bhp	6.2	0.5550	0.2100	2.640	0.0173	0.0111	1.56
mass	7.4	0.9970	0.0069	14.520	-0.0008	0.0050	-1.59
loa							
grt	14.4	1.0507	0.0790	13.250	-0.0019	0.0089	-2.17
bsize							

(b). Multiple regression coefficients.

(i). fp on sqrt bhp, mass, grt, loa - R^2 = 35.2%

	Estimate	SE	t
constant	0.97300	0.25100	3.87
sqrt bhp	0.02400	0.01370	1.76
mass	0.00103	0.00100	1.02
grt	-0.00350	0.00013	-2.69
loa	-0.01890	0.02000	-0.94

(ii), fp on sqrt bhp, mass, grt, loa, bsize - R^2 =42.5%

	Estimate	SE	t
constant	0.4140	0.4040	1.02
sqrt bhp	0.0319	0.0137	2.33
mass	0.0012	0.0009	1.23
grt	-0.0035	0.0012	-2.84
loa	-0.0245	0.0191	-1.29
bsize	0.1880	0.1100	1.71

Note: G.E. is greater than.

Appendix 3.2: The effect of engine power, vessel mass, length, gross tonnage and board size on fishing power -vessels with BHP G.E. 364 BHP.

(a) Linear regression

	R^2	Constant	SE	t	Slope	SE	t
sqrt bhp		(Residual variance exceeds variance of fishing power).					
mass	3%	0.9685	0.0546	17.740	-0.0005	0.0004	-1.21
loa		(Residual variance exceeds variance of fishing power).					
grt	18.9	1.0353	0.063	16.370	-0.0016	0.0007	-2.23
bsize		(Residual variance exceeds variance of fishing power).					

(b). Multiple regression coefficients.

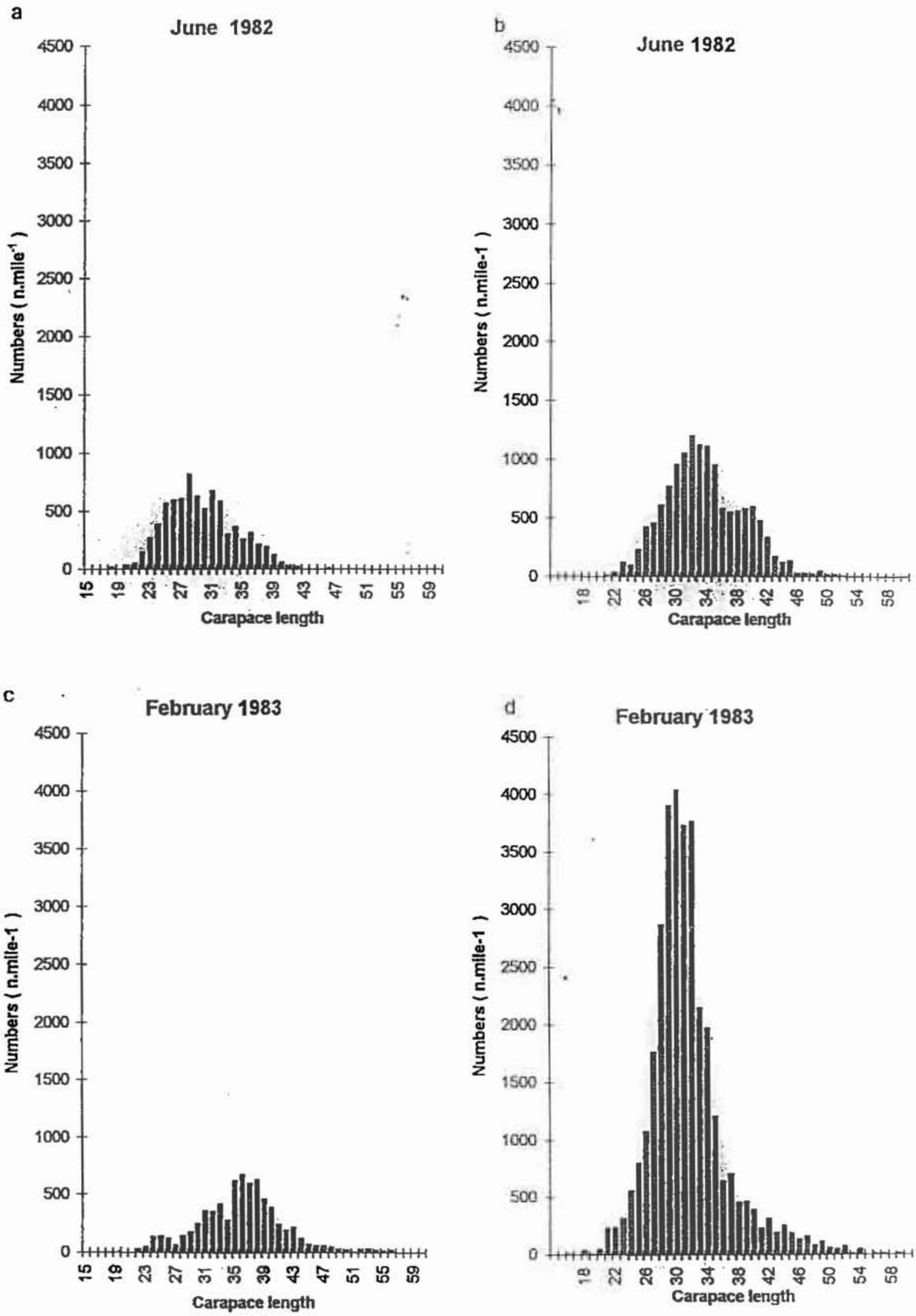
(i). fp on sqrt bhp, mass, grt, loa - $R^2 = 9.6\%$

	Estimate	SE	t
constant	1.09900	0.34000	3.23
sqrt bhp	-0.02000	0.02530	-0.80
mass	-0.00013	0.00090	-0.14
grt	0.00250	0.00130	-1.91
loa	0.02260	0.00215	1.05

(ii), fp on sqrt bhp, mass, grt, loa, bsize - $R^2 = 0.8\%$

	Estimate	SE	t
constant	1.0030	0.7010	1.43
sqrt bhp	-0.0180	0.0299	-0.60
mass	-0.0001	0.0097	-0.11
grt	-0.0025	0.0014	-1.77
loa	0.0215	0.0234	0.92
bsize	0.0250	0.1580	0.16

Appendix 4.0: Comparison of P.latisulcatus recruitment in the northern and southern (Cowell) areas of Spencer Gulf. South - a & c, North - b & d.



APPENDIX 4.1

The relationship between nominal cpue and recruitment in Spencer Gulf over 23 Blocks with ncpue = 18.2 +0.000084 recruits, r=0.89

Analysis of Variance

Source	DF	SS	MS	F	p	%V
Regression	1	511.51	511.51	26.65	0	79.2
Error	7	134.38	19.2			
TOTAL	**8**	**645.89**				

Appendix 4.2: **Spawner Recruit relationship using exponential model.**

Nonlinear regression analysis

Response variate: recruits
Explanatory : spawners
Fitted curve : A + B*R**X
Constraints : R<1

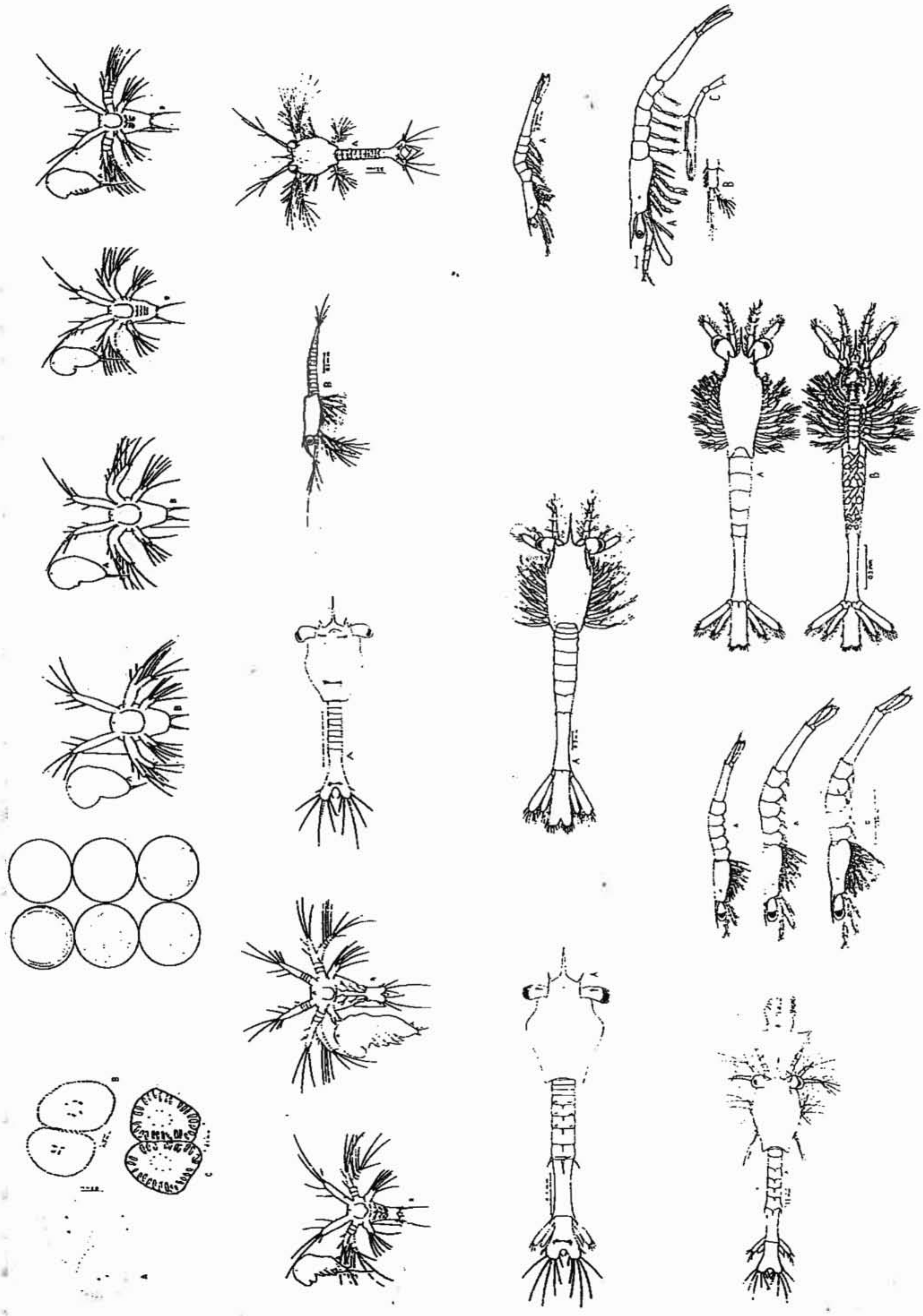
Summary of analysis

	d.f.	SS	MS	VR
Regression	2	1542549	771275	16.84
Residual	7	320637	45805	
Total	9	1863186	207021	

Estimates of parameters

	Estimate	SE
R	0.745	0.177
B	-1.84E+12	3.20E+13
A	2494.8	96.1

Appendix 4.3 : **Prawn life cycle - metamorphic changes from egg to postlarvae.**



APPENDIX 5

Analysis of Variance of numbers of *P. latisulcatus* larvae (zoea 1 and 2) at Transect 1 (north) and Transect 2 (south) in mid regions of Spencer Gulf from October 1992 to April 1994.

A. Test of Transect effect-log transformed

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Month	6	128.85	21.47	176.10	<.001
Lin	1	2.74	2.74	22.47	<.001
Quad	1	110.86	110.86	909.06	<.001
Cub	1	2.96	2.96	24.29	<.001
Deviations	3	12.29	4.10	33.59	<.001
Transect	1	10.91	10.91	89.48	<.001
Month.Transect	6	43.33	7.22	59.22	<.001
Lin.Transect	1	7.03	7.03	57.66	<.001
Quad.Transect	1	8.95	8.95	73.35	<.001
Cub.Transect	1	9.95	9.95	81.55	<.001
Deviations	3	17.41	5.80	47.58	<.001
Residual	14	1.71	0.12		
Total	27	184.80			

B. Transect 4- log transformed

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Month	6	50.27	8.38	59.82	<.001
Lin	1	0.50	0.50	3.55	0.102
Quad	1	28.41	28.41	202.89	<.001
Cub	1	1.03	1.03	7.33	0.030
Deviations	3	20.33	6.77	48.38	<.001
Residual	7	0.98	0.14		
Total	13	51.24			

C. Transect 1- log transformed

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Month	6	121.92	20.32	195.65	<.001
Lin	1	9.27	9.27	89.30	<.001
Quad	1	91.39	91.39	879.97	<.001
Cub	1	11.88	11.88	114.39	<.001
Deviations	3	9.37	3.12	30.08	<.001
Residual	7	0.73	0.10		
Total	13	122.65			

Nonlinear regression analysis of log number and number of zoea 1 and 2 over Transects using a double Fourier model from 19/11/92 (time 0) to 23/4/93 (time 186 day); A & B - Double Fourier, C - Gaussian, D - double Gaussian models.

(A) Response variate: log number
Fitted Curve: A + B*sin (2pi (X-E) / W) + C*sin (4pi (X - F) / W)

	d.f.	s.s.	m.s.	v.r.
Regression	11	182.332	16.576	107.45
Residual	16	2.468	0.154	
Total	27	184.801	6.844	

Percentage variance accounted for 97.7

(B) Response variate: number
Fitted Curve: A + B*sin (2pi (X-E) / W) + C*sin (4pi (X - F) / W)

	d.f.	s.s.	m.s.	v.r.
Regression	11	2050647.	186422.	11.78
Residual	16	253306.	15832.	
Total	27	2303953.	85332.	

Percentage variance accounted for 81.4

(C) Response variate: number. Unsuccessful optimization
Fitted Curve: A + B*Gauss (X - M) /S)

	d.f.	s.s.	m.s.	v.r.
Regression	7	1986157.	283737.	17.86
Residual	20	317796.	15890.	
Total	27	2303953.	85332.	

Percentage variance accounted for 81.4

(D) Response variate: number. Optimization not converged.
Fitted Curve: A + B*Gauss (X - M) /S) + C*Gauss ((X -N) /S)

	d.f.	s.s.	m.s.	v.r.
Regression	11	2196460.	199678.	29.72
Residual	16	107494.	6718.	
Total	27	2303953.	85332.	

Percentage variance accounted for 92.1

Nonlinear fit to *P. latisulcatus* larvae (zoea 1 and 2) in Transect 4 and 1, Spencer Gulf. A - Transect 4; B- Transect 1. Time is days from 19/10/92 (day 0) to 23/4/93 (day 186).

A. Transect 4

(i) Double Fourier model using no.

	d.f.	s.s.	m.s.	v.r.
Regression	5	62694.	12538.7	63.40
Residual	8	1582.	197.8	
Total	13	64276.	4944.3	

Percentage variance accounted for 96.0

(ii) Double Fourier model using log no.

	d.f.	s.s.	m.s.	v.r.
Regression	5	50.242	10.05	80.49
Residual	8	0.999	0.125	
Total	13	51.24	3.94	

Percentage variance accounted for 96.8

(iii) Double gaussian model using no.

	d.f.	s.s.	m.s.	v.r.
Regression	5	53029.	10606.	7.54
Residual	8	11247.	1406.	
Total	13	64276.	4944.	

Percentage variance accounted for 71.6

B. Transect 1

(i) Double Fourier model using no.

	d.f.	s.s.	m.s.	v.r.
Regression	5	1547950.	309590.	9.84
Residual	8	251724.	31466.	
Total	13	1799674..	138436.	

Percentage variance accounted for 77.3

(ii) Double Fourier using log no.

	d.f.	s.s.	m.s.	v.r.
Regression	5	121.18	24.236	131.94
Residual	8	1.47	0.1837	
Total	13	122.65	9.435	

Percentage variance accounted for 98.1

(iii) Double Gaussian using no.

	d.f.	s.s.	m.s.	v.r.
Regression	5	1703427.	340685.	28.32
Residual	8	96247.	12031.	
Total	13	1799674.	138436.	

Percentage variance accounted for 91.3

F-test comparisons of models fitted to juvenile prawn densities at False Bay sampled from 13/12/92 to 21/06/1993 - dgaussian means-M=2.22 ± 0.07, M= 4.12 ± 0.07; Gaussian mean M=3.28 ± 0.09 month.

Model	RSS	df	RMS	RSS diff/dfd	F (2,111)	p	% v
dgaussian	850199	111	7659	100157.50	13.08	<0.005	64.3
gaussian	1050514	113					56.6
total	2485591	116					

APPENDIX 9

ANOVA of mean numbers of prawns on the Western side of Spencer Gulf, February-March 1993.

Source of variation	d.f	s.s.	m.s	v.r.	F pr.
Site	12	1500295	125025	49.73	<.001
Lin	1	28113	28113	11.18	0.001
Quad	1	45562	45562	18.12	<.001
Cub	1	498432	498432	198.25	<.001
Deviations	9	928188	103132	41.02	<.001
Period	2	34278	17139	6.82	0.002
Site Period	24	264671	11028	4.39	<.001
Lin Period	2	54022	17011	10.74	<.001
Quad Period	2	2704	1352	0.54	0.586
Cub Period	2	5819	2909	1.16	0.320
Deviations	18	202126	11229	4.47	<.001
TOTAL	116	1995348			

Tables of means

Variate: Number

Grand mean 158.2

Site	14	13	12	11	10	9	8
	0.4	0.7	370.2	292.4	167.3	61.2	157.7
	7	6	5	4	3	2	
	243.8	158.6	156.0	63.2	79.0	306.2	

Period	1	2	3
	137.7	157.3	179.6

Standard errors of differences of means

Table	Site	Period	Site*Period
rep.	9	39	3
s.e.d.	23.64	11.35	40.94

Appendix 10 : Harvest model 1.0, Spencer Gulf

```
variate length;!(20...65)
calc nunits=nval(length)
Unit[nunits]

" PROGRAM HARV 1.00- Ray Correll and Neil Carrick"
" THIS PROGRAM SERIES HV 1.00...HV 5.01 has been enhanced"

"HARVEST SIMULATION OF VALUE/HR TRAWLING -Group 1-stations
   N21...N22, 66,67 and 68 information entered dataflex and
   down loaded to genstat
   INPUT DATA:
      . real time size and measurements from sea-12 regions
      . growth and allometry
      . price structure-from industry averages/grade
      . scalar-mortality (M)=0.08)
      . catchability indices"

" Set a few constants"
scalar nmonths;9 "This is the number of months of growth"
calc nm_1=nmonths+1 "This is generally the vector length"

"Allometry information"
pointer intercept;!p(male_i,female_i)
pointer slope;!p(male_s,female_s)
scala intercept[];-6.705,-6.347
scalar slope[];2.764,2.657

"Set time of start-from April 14 to simulate each month"

scalar start;3.5;extra=' 3.5 represents April 14'
variate mpoint;!(1...nm_1)
calc mpoint=int(start)+mpoint
calc mpoint=mpoint-12*(mpoint>12)
calc mpoint=mpoint-12*(mpoint>12)
"pity about there being no modulo function!"
""
"Vulnerability, starting in January-
vari vulner; !(0.8,0.9,1,1,.95,.85,.6,.4,.5,.8,.9,.9)
"map onto simulated months"
calc vulnerability=vulner$[mpoint]

"Set the mortality"
scalar mortality;0.08

fact[la=!t(male,female)]sex


"Set growth coefficients for Spencer Gulf"
```

```
fact[la=!t(freedom,sin1,cos1,sin2,cos2)]trm
table[c=trm,sex]coef;!v(12.58,27.07,17.57,25.62,7.51,12.59,4.35,2.82,-17.3
   ,-17.13)
poin cf;!p(mfree,ffree,msin1,fsin1,mcos1,fcos1,msin2,fsin2,mcos2,fcos2)
scal cf[]
equate coef;cf

"Grade of prawns in number per pound"
text grd;!t('>50','30-50','25-30','20-25','15-20','10-15','6-10','<6')
fact[la=grd]grade
table[c=grade]price;!v(0,4.0,6.0,7.5,9.5,13.,14.5,15.00)          "Dollars per kg"
print price;d=2
"set grade limits to weight in grams "

calc limits=454/!v(50,30,25,20,15,10,6,1)
calc pi=3.14159
calc theta0=start/12*2*pi

" Read in the initial data using in2=filename"
open 'prsdbg1a.90';2
pointer count;!p(male_n,female_n)
read[c=2;e=*]length,count[]
print length,count[];d=0
close 2

"calc weights"
pointer weight;!p(male_w,female_w)
pointer weightp;!p(male_p,female_p);extra=' predicted weights'
calc weight[]=exp(intercept[])*length**slope[]

variate[nm_1]biomass,biovalue,femalevalue,malevalue,femalemass,malemass
pointer[2]increase
   "This uses the idea that the weight increase of a prawn is independent
     of its length"
scal thstai,dcos1,dsin1,dcos2,dsin2,increase[]
scalar survival;1

for month=0...nmonths
    "Calculate growth since start"
    calc inc=month/12
    calculate index=month+1
    calc thetai=(start/12+inc)*2*pi
    calc dcos1=-(cos(thetai)-cos(theta0))/2/pi
    calc dsin1=(sin(thetai)-sin(theta0))/2/pi
    calc dcos2=-(cos(thetai*2)-cos(theta0*2))/4/pi
    calc dsin2=(sin(thetai*2)-sin(theta0*2))/4/pi
    calc increase[1,2]=inc*cf[1,2]+dcos1*cf[3,4]+dsin1*cf[5,6]\
      +dcos2*cf[7,8]+dsin2*cf[9,10]
    "in the above, inc is the growth time"

    calc weightp[]=weight[]+increase[]

    "Allow for natural mortality: survival is initial declared as 1"
```

```
    calc wtedwt[1,2]=weightp[]*count[]*survival
    "Survival is now decreases ready for the next month"
    calc survival=survival*(1-mortality)

   "The scalars are copied into vectors for printing and plotting:

      location indicates their position in the vector"
   calc location=1+month
   calc biomass$[location]=sum(vsum(wtedwt))
   calc malemass$[location]=sum(wtedwt[1])
   calc femalemass$[location]=sum(wtedwt[2])

  "Calculate the grade of each prawn"
   sort[weightp[1];gradem;limits=limits]
   sort[weightp[2];gradef;limits=limits]

   "Tabulate the weights by commercial grade"
   table[c=gradem]tvalue[1]
   table[c=gradef]tvalue[2]
   tabu wtedwt[1];tvalue[1]
   tabu wtedwt[2];tvalue[2]

   "make compatible to price which is a table"
   table[c=grade]tdummy[1,2]
   equate tvalue;tdummy

   "Calculate the value at the current month of the iteration"
   "this allows a 20 % price increase from October to December"
   "If month is October,November or December allow 20% premium"
   calc mp = month + 1
   scal premium
   calc prem=1 + (mpoint$[mp]>1) * 0.20
   equate prem;premium
   calc ttvalue[1,2]=tdummy[]*price*premium/1000
   calc malevalue$[location]=sum(ttvalue[1])
   calc femalevalue$[location]=sum(ttvalue[2])

   endfor

calc biovalue=malevalue+femalevalue

"Set up month labels for printing"
text moname;\
!t(Jan,Feb,Mar,Apr,May,Jun,Jul,Aug,Sep,Oct,Nov,Dec)
text[1] mtname[1...12]
text[nm_1] mname
equate moname;mtname
equate mtname[mpoint];mname
calc when=!v(0...nmonths)+start

graph biomass; when
graph biovalue;when
```

```
"Allow for differential vulnerability in different months"
calc trawlmass,trawlvalue=biomass,biovalue*vulnerability
"print out size (grades, means, approximate no/bucket) plus
value etc"
print when,mname,trawlmass,trawlvalue
graph trawlmass;when
graph trawlvalue;when
calc malenumber,femalenumber=sum(count[])*(1-mortality)**!(0...nmonths)
calc bothnumber=malenumber+femalenumber
"Calculate the weight of a typical prawn"
calc maleweight,femaleweight,bothweight=malemass,femalemass,biomass/\
  malenumber,femalenumber,bothnumber
"Calculate the length of a typical prawn"
 calc malelength,femalelength\
     =exp((log(maleweight,femaleweight)-intercept[])/slope[])
     calc\
     bothlength=(malelength*malenumber+femalelength*femalenumber)/bothnumbe
     calc\
     malegrade,femalegrade,bothgrade=454/(maleweight,femaleweight,bothweigh
     calc\
     maleprice,femaleprice,bothprice=malevalue,femalevalue,biovalue/\
 malemass,femalemass,biomass
 calc bucket=7200/bothweight

print mname,biomass,biovalue,maleleng,femalelength,malegrade,femalegrade,\
bothgrade;9
print mname,biomass,biovalue,bucket,maleweight,femaleweight,bothweight;9
print mname,malemass,femalemass,malevalue,femalevale;9
print mname,malenumb,femalenum,bothnumb,malelength,femalelength,bothlength
print mname,malegrade,femalegrade,bothgrade,maleprice,femaleprice,bothpric
```