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The extent of interaction between the scallop and prawn fleets in the Shark Bay scallop managed fishery

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The Extent of Interaction between the Scallop and Prawn Fleets in the Shark Bay Scallop Managed Fishery

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ABSTRACT

The Shark Bay Managed Scallop Fishery is Western Australia's most important scallop fishery with an annual value of between $2 and $58 million. In addition to this the fishery is an important source of regional employment with approximately 160 skippers and crew employed during the 2005 season. Two separate fleets are permitted to fish for scallops in this fishery, the first consisting of dedicated scallop fishing vessels (Class A licences) and the second of prawn fishing vessels (Class B licences) that are allowed to take scallops under a catch sharing arrangement. Concerns exist over the interactions between these two fleets and in particular how the catch of the Class A fleet is affected by the fishing activity of the Class B fleet.

This thesis discusses the results obtained from a statistical analysis of the relationship between the fishing effort used by the Class B fleet and the size of the subsequent scallop catch. Geostatistical estimation (kriging) has been used on survey data to allow for comparisons to be made with catch and fishing effort data. Spatial maps of these data have been constructed and investigated for the presence of spatial patterns. Measurements of correlation and spatial association have also been used to quantify the relationship between the level of fishing effort used by the Class B fleet and the size of the scallop catch achieved by the Class A fleet and by both fleets combined. Finally, an investigation has also been conducted on the effect that fishing by the Class B fleet has on the subsequent scallop recruitment.

The results presented in this thesis do not indicate the presence of a marked or consistent relationship between the level of fishing effort applied by the Class B fleet and the size of the subsequent scallop catch during the 2000 to 2005 fishing seasons. As such, this thesis has found no evidence that the fishing activity of the Class B fleet, over the entire season, during the spawning period or prior to the start of scallop fishing, has a direct effect on the scallop catch achieved by the Class A fleet.

USE OF THESIS

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Date 21/08/07

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CONTENTS

List of Figures

List of Tables

1. Introduction

1.1. *Background and Significance*

The Shark Bay Scallop Managed Fishery, located in the waters of Shark Bay off the coast of Western Australia's Gascoyne region, is the state's most important scallop fishery. The southern saucer scallop (*Amusium balloti*) is caught in this fishery by vessels using otter trawl. Within the fishing region actual trawling for scallops occurs in the waters east of the bay's outer islands, in depths of between 16 m and 40 m. In terms of meat weight, the total annual catch for the fishery, from 1983 to 2005, has ranged from 121 to 4,414 tonnes with an average of 734.3 tonnes as illustrated by the plot in Figure 1. During this period the value of the fishery has ranged between $2 and $58 million per annum (Kangas et al., 2006). Although the annual catch varies dramatically, as is the case with most scallop fisheries, Shark Bay is Western Australia's most profitable scallop fishery despite the fact that in some years larger catches have been recorded in other fisheries. Most of the Shark Bay scallop catch is marketed to the lucrative south-east Asian market as frozen scallop meat (Sporer and Kangas, 2005).

The western population of saucer scallop is distributed along most of the Western Australian coast and is typically restricted to areas of bare sand located in more sheltered environments. This species has a rapid early growth and in Shark Bay most appear to live no more than two years and generally grow to a maximum size of approximately 115 mm (Kangas et al., 2006). The reproductive cycle for Shark Bay scallops begins with the onset of gametogenesis in late March or early April, with spawning taking place between 4 to 8 weeks later. The larval phase of the saucer scallop lasts between 12 and 24 days and the success of this phase appears to be determined by the prevailing oceanographic events. Following this, the juvenile scallops settle out as spat over a period of several days before attaching to the substrate a week after settlement (Kangas et al., 2006). Growth of new recruits is rapid with scallops derived from the beginning of the spawning season reaching sizes of around 50-60 mm in shell height by November and a suitable size for harvest (>90 mm shell length) is reached within approximately one year (Kangas et al., 2006).

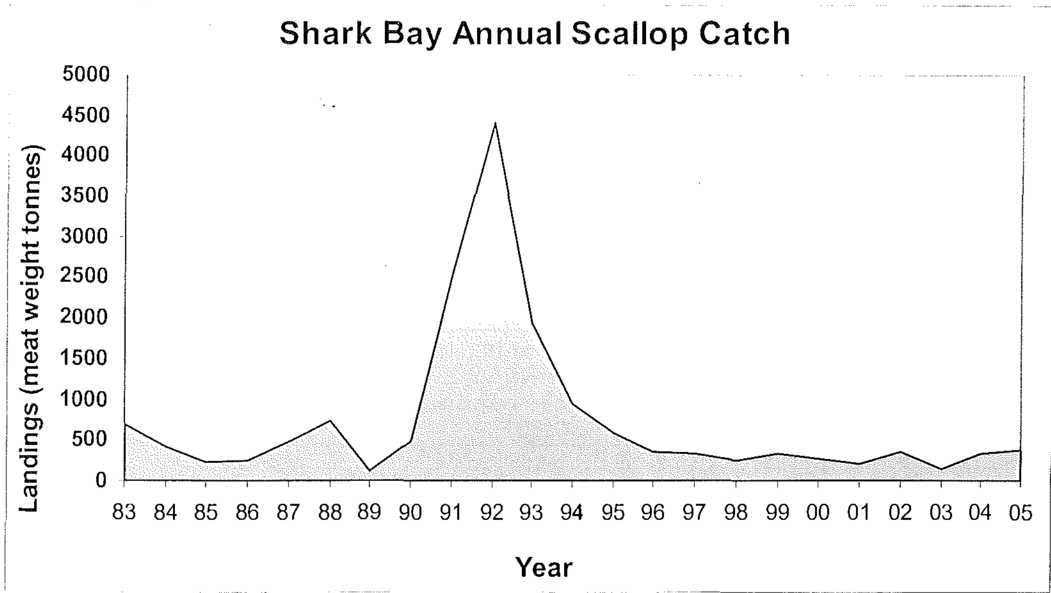

Figure 1: Shark Bay Managed Fishery total annual scallop catch, 1983 – 2005

The Shark Bay scallop fishery is a relatively young fishery with landings of scallops first reported in 1966. For several years scallops were only caught as the by-catch of Shark Bay's prawn fishing fleet with the species first being targeted for commercial purposes in the area during the late 1960s due to a brief increase in catch. By the 1980s the number of vessels trawling for scallops in the fishery rose dramatically. Several factors including improvements to processing the catch at sea, increases in price and an apparently plentiful stock made fishing in Shark Bay increasingly profitable (Harris et al., 1999). The resulting increase in fishing effort on the scallop stock was further compounded by the Shark Bay prawn trawlers which began retaining scallops caught while trawling for prawns. Following a biological review the Shark Bay fishery was declared a limited entry fishery in 1987, restricted to 14 dedicated scallop vessels (Class A licences) and 35 vessels that fish for prawns in the Shark Bay Prawn Managed Fishery (Class B licences) but are also allowed to take scallops under a catch sharing arrangement (Harris, et al., 1999). Approximately 70% of the total scallop catch is taken by the dedicated scallop fleet. The Shark Bay prawn fleet was later reduced to 27 vessels to limit the available effort that could be used on prawn stocks and to improve vessel economics (Kangas, et al., 2006).

In 2005 the total scallop landings for the Shark Bay fishery were 384.6 tonnes of meat weight with an estimated value, to the fishers, of $6.5 million (Sporer and Kangas, 2006). Of the total catch, 217.5 tonnes (56.6%) of meat weight were caught by Class A vessels with the remaining 167.1 tonnes caught by Class B vessels. The fishery has a considerable social effect on the region with approximately 160 skippers and crew employed for the 2005 season (ibid). There are also numerous processing and support staff employed at Carnarvon and Geraldton making this and other fisheries a major source of employment for the Gascoyne region.

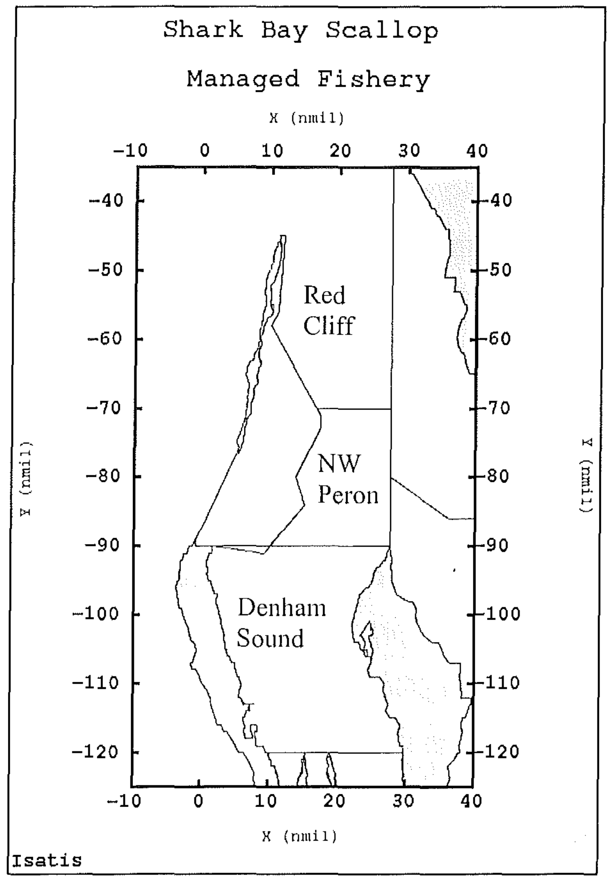

Figure 2: The Shark Bay Scallop Managed Fishery

Management of the fishery is currently achieved by regulating fleet sizes, season and area closures, gear controls and crew sizes. The aim of these management techniques is to allow the fishing fleets to catch scallops at the best possible size and condition while maintaining breeding stock levels (Sporer and Kangas, 2005). Throughout the season permanent closure areas are in place for both fleets and temporary closures are implemented in other areas such as Denham Sound. The Class A vessels are permitted to fish for 24 hours a day during the scallop season while the Class B vessels are restricted to fishing at night. The fishery normally closes in November with the season's end date usually aligned with the closure of the Shark Bay Prawn Managed Fishery. The Class A fleet vessels however generally stop fishing before the closure date due to low scallop catch rates (Kangas, et al., 2006). The opening dates for the fishery differ considerably between the two fleets with the fishing season for Class B vessels beginning in March while for the Class A vessels the season does not commence until April or May.

Concerns have been raised over interactions between the two fleets and the effects resulting from the different commencement dates for each fleet. Subsequently, it has been proposed that the fishing activities of the Class B fleet, especially before the beginning of the scallop fishing season, may have a harmful effect on the catch that the Class A fleet achieves. It has been suggested that any possible detrimental effect on the scallop catch may be a result of smaller scallops being killed as a consequence of trawling conducted by the Class B fleet or that scallops caught, before the start of the season, have a low survival rate after being returned to the water.

In this thesis we seek to answer several questions regarding the interaction between the Class A and Class B fleets in Shark Bay. Firstly, we will investigate whether high levels of pre-season fishing effort applied by the prawn fleet have a negative impact on size of the subsequent scallop catch. This thesis will also determine how well areas of high predicted scallop catch match the actual scallop catch and if trawling carried out by the Class B fleet during scallop spawning impacts negatively on the settlement of scallops.

This thesis focuses on the extent of interaction between the Class A and Class B fishing fleets in the Shark Bay Scallop Managed Fishery. An understanding of the statistical relationship between the fishing effort and scallop catch of these fleets will assist the Western Australian Department of Fisheries in making decisions regarding the management of the fishery. In particular, it will aid in choices regarding the implementation of input controls such as seasonal and area closures. It is also hoped that the findings of this thesis will help ensure equitable treatment for the two fleets in addition to supporting the maintenance of good relations between the fleets.

1.2. *Objectives*

In this thesis we discuss the results obtained from a statistical analysis of the relationship between the fishing activity of the Class B fleet and the size of the subsequent scallop catch in the Shark Bay fishery using data for the 2000 to 2005 fishing seasons. Several variables have been investigated at locations across the Shark Bay fishing grounds to determine any spatial associations or disassociations between them. In particular, variables of interest include the total fishing effort of the Class B fleet, for both the entire season and before the start of the scallop season, and the total scallop catch, for both fleets combined and the Class A fleet individually. In addition to this the fishing effort used by the Class B fleet during the scallop spawning season has been compared to the density of recruit scallops, as indicated by the following scallop survey estimates.

Several different data sets have been used to conduct the analysis presented in this thesis. Firstly, the logbook data from the 2000 to 2005 fishing seasons, which are recorded by fishers, for both the Class A and Class B fleets have been used extensively. A subset of these logbook data consisting of the records of the fishing carried out by the Class B fleet prior to the start of the scallop fishing season have been utilized to investigate the effects of pre-season fishing effort. Finally, in this thesis use was also made of the data from the 1999 to 2005 Shark Bay scallop surveys, conducted by the Department of Fisheries.

As the data sets considered in this thesis are spatial in nature, techniques from geostatistics and spatial statistics have been used to analyse these data. Geostatistical estimation (Kriging) has been carried out on survey data to allow for comparisons to be made with catch and effort data. Spatial maps of these estimates and the variables identified above have been constructed and investigated for spatial patterns. Measurements of correlation and spatial association have also been calculated to quantify the relationship between the fishing effort of the Class B fleet and scallop catch.

1.3. Thesis Outline

Chapter 2 presents the theoretical framework relevant to this thesis. This includes correlation analysis, the random function model, variography, kriging methods and measures of spatial association. Chapter 3 then describes the data sets used in the thesis and a brief exploratory data analysis is carried out on the variables of interest. The results of the main analysis are presented in Chapter 4 of the thesis. This includes the kriging of survey data, investigations of spatial maps, the results of correlation analysis and indices of spatial association. In addition to this the results of an investigation using cross-variography are described in Appendix A of the thesis. Chapter 5 provides a discussion of these results and details the conclusions of the thesis.

1.4. Software

Several software packages were used to carry out the analysis described in this thesis. These packages are listed below.

ISATIS (Geovariances):	Variography, estimation, spatial maps, summary statistics and moving window statistics.
SPSS (SPSS Inc.)	Exploratory Data Analysis, histograms and calculation of correlation coefficients.
Excel (Microsoft):	Data preparation and manipulation, graphical representation of data/results and other calculations.
Word (Microsoft):	Compilation of the thesis.

2. Theoretical Framework

2.1. *Notation*

The notation used to describe geostatistical formulae can differ somewhat between texts. The notation used in this report and throughout the project will follow that used in Goovaerts (1997).

2.2. *Correlation Analysis*

Correlation analysis is a method used to determine the strength of the linear relationship that exists between variables. In general usage correlation is a measure of the interdependence among data with two or more variables (Montgomery et al., 2003). For correlation analysis it is assumed that the data points (x_i, y_i) for $i = 1, 2 \ldots, n$ are values of a pair of random variables whose joint density is given by $f(x, y)$. There are several different methods used to measure the relationship between these variables including the scatter plot, Pearson's correlation coefficient and Spearman's correlation coefficient.

The scatter plot is a plot of the ordered pairs (x_i, y_i) on a two-dimensional coordinate system. This plot provides a graphical means for determining if a linear relationship exists between two variables. The variables are said to have a strong degree of linear correlation if the points lie close to a straight line. If this straight line has a positive slope it is said that the variables have a positive linear correlation while a negative slope indicates that the variables have a negative linear correlation. If the straight line has a slope of 0 there is no linear correlation between the two variables.

The strength of any linear correlation present in the data can be measured numerically in terms of the correlation coefficient. Pearson's correlation coefficient provides an interpretation of this measure. Essentially it is a dimensionless measure of the interdependence between two variables with values of 1 or -1 indicating a perfect positive or negative linear correlation respectively and a value of 0 indicating the absence of linear correlation. This index, also called the product moment correlation coefficient, is denoted by r and is computed as:

$$r = \frac{\sum_{i=1}^{n}\left[(y_i - \bar{y})(x_i - \bar{x})\right]}{\sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2 \sum_{i=1}^{n}(x_i - \bar{x})^2}}$$

where $\bar{x}$ and $\bar{y}$ are the means of the x and y variables respectively and n is the number of pairs involved in the sample (Montgomery, D. et al., 2003). Another method for calculating a correlation coefficient is the Spearman's rank correlation coefficient which can be used to measure the association between two variables measured on an ordinal scale. In order to calculate this value the x and y variable must each be assigned a rank from 1 to n. The Spearman's correlation coefficient r_s is calculated as:

$$r_s = 1 - \frac{6\sum_{i=1}^{n} d_i^2}{n(n^2 - 1)}$$

where d_i is the difference between the i^{th} pair of ranks and n is the number of pairs (Weimer, C., 1993). In practice this formula can also be used when tied ranks are present in the data set. For every case of tied ranks, each of the tied observations is assigned the average of the ranks that would have resulted if there had been no ties.

If $n > 10$ and the population correlation coefficient ρ_s of the ranked data is 0 then the distribution of r_s is approximately normal with a mean of 0 and a standard deviation given by:

$$\sigma_{r_s} = \frac{1}{\sqrt{n-1}}$$

As a result it can be determined if $\rho_s \neq 0$ by finding the z value for r_s under the assumption that $\rho_s = 0$. The value for the test statistic for testing the null hypothesis $\boldsymbol{H_0}$: $\rho_s = 0$ is given by:

$$z = \frac{r_s - 0}{1/\sqrt{n-1}} = r_s\sqrt{n-1}$$

and the null hypothesis is rejected at level of significance ∂ if $z > z_{\partial/2}$ or $z < -z_{\partial/2}$.

2.3. Geostatistics

Geostatistics is a relatively young field of statistics, whose theoretical foundations were established by G. Matheron (Rivoirard, J., et al., 2000). This branch of statistics makes use of not only the information on the value of an attribute of interest but also of the location at which that value occurred. Such spatial information is typically found in earth sciences data sets however the applications of geostatistics have expanded to a considerable number of fields. Essentially geostatistics provides a set of statistical tools that can be used to include the spatial coordinates of observations when analysing data (Goovaerts, 1997). These tools offer methods of describing the spatial continuity of variables of interest and provide modified forms of regression techniques that take advantage of this continuity (Isaaks and Srivastava, 1989).

Geostatistics can be used as a means to describe spatial patterns and to use this information to estimate the value of attributes of interest at unsampled locations (Goovaerts, 1997). Geostatistics have been used to analyse data that arise in many different fields such as mining, environmental sciences, soil sciences, petroleum exploration and oceanography. More recently this branch of statistics has been applied to the estimation of various marine biological resources including shellfish (Rivoirard, J., et al., 2000).

2.3.1. The Random Function Model

Geostatistics is largely based upon the concept of random function, whereby the set of unknown values is considered as a set of spatially dependent random variables. The local uncertainty about the attribute value at any particular location **u** is modelled through the set of possible realisations of the random variable at that location. The random function concept permits the structures in the spatial variation of the attribute to be accounted for. The set of realisations of the random function models the uncertainty about the spatial distribution of the attribute over the entire study region (Goovaerts, 1997).

A random function is defined as a set of typically dependent random variables $Z(\mathbf{u})$, for each location $\mathbf{u}$ in the study region. To any set of N locations $\mathbf{u}_k$, $k = 1,\ldots,N$ corresponds to a vector of N random variables that is characterised by the N-variate cumulative distribution function (cdf):

$$F(\mathbf{u}_1,\ldots,\mathbf{u}_N; z_1,\ldots,z_N) = Prob\{Z(\mathbf{u}_1) \leq z_1,\ldots,Z(\mathbf{u}_N) \leq Z_N\}$$

The multivariate cdf describes the joint uncertainty about the N values $z(\mathbf{u}_1),\ldots,z(\mathbf{u}_N)$. The set of all such N-variate cdfs, for all positive integers N and for every possible choice of locations $\mathbf{u}_k$, forms the spatial law of the random function $Z(\mathbf{u})$. Generally, the analysis is limited to cdfs involving no more than two locations at a time and their corresponding moments. The one point cdf is given by:

$$F(\mathbf{u};\mathrm{z}) = \mathrm{Prob}\ \{\mathrm{Z}(\mathbf{u}) \leq z\} = E\{I(\mathbf{u};z)\}$$

and the two point cdf by:

$$F(\mathbf{u},\mathbf{u}';\mathrm{z},\mathrm{z}') = \mathrm{Prob}\ \{\mathrm{Z}(\mathbf{u}) \leq z,\ Z(\mathbf{u}') \leq z'\} = E\{I(\mathbf{u};z)\cdot I(\mathbf{u}';z')\}$$

with the random variable $I(\mathbf{u};z)$ equal to 1 if $Z(\mathbf{u}) \leq z$ and 0 otherwise (Goovaerts, 1997).

2.3.2. Spatial Data Analysis

Spatial data analysis involves studying and modelling the spatial patterns and continuity between attributes of interest recorded at different locations. Before starting a spatial analysis of any data set an exploratory data analysis must be carried out first so that a better understanding of the nature of the data can be attained. This data analysis may begin with calculating the summary statistics and include graphical analysis techniques so that information relating to the nature and distribution of the attributes of interest can be obtained and possible outlying data can be identified and further investigated.

After a sufficiently detailed exploratory data analysis has been carried out exploratory spatial data analysis should be performed so that any spatial patterns that may be present in the data can be investigated and modelled. This involves first creating spatial maps of the data which are created by plotting the location of each datum on a coordinate system along with an indication as to its value, usually through a colour coded scale. These post plots are used to display the spatial spread of the data set and to visually investigate for connectivity of values between locations.

Variography is then carried out to analyse the spatial variability of the data. This involves creating semivariograms which are used to measure the dissimilarity between pairs of data at different distances. They are computed as half the average squared difference between the attribute values of every data pair:

$$\gamma(\mathbf{h}) = \frac{1}{2N(\mathbf{h})} \sum_{\alpha=1}^{N(\mathbf{h})} [z(\mathbf{u}_\alpha) - z(\mathbf{u}_\alpha + \mathbf{h})]^2$$

where $[z(\mathbf{u}_\alpha) - z(\mathbf{u}_\alpha + \mathbf{h})]$ is a **h**-increment of attribute z and $N(\mathbf{h})$ is the number of pairs of data locations separated by vector **h** (Goovaerts, 1997).

Semivariogram maps and directional semivariograms are used to determine if the spatial variability of the data depends upon direction as well as distance and if so to identify the directions of maximum and minimum continuity. These semivariograms are then used to model the spatial variability of the data and the resulting models are utilized in a number of estimation methods. The semivariogram models that are used in the project will consist of at most three structures. The model types, given below, will be used with a and h denoting the practical range and the distance from the origin respectively and C is a coefficient which gives the order of magnitude of the variability along the vertical axis called the "sill".

Nugget structure:

$$\gamma(\mathbf{h}) = \begin{cases} 0 & \textit{if } \mathbf{h} = 0 \\ C & \textit{otherwise} \end{cases}$$

Spherical structure:

$$\gamma(\mathbf{h}) = \begin{cases} C\left[3\mathbf{h}/(2a) - \mathbf{h}^3/(2a^3)\right] & \textit{if } \mathbf{h} < a \\ C & \textit{if } \mathbf{h} \geq a \end{cases}$$

Exponential structure:

$$\gamma(\mathbf{h}) = C\left[1 - \exp(-2.996\mathbf{h}/a)\right]$$

Cubic structure:

$$\gamma(\mathbf{h}) = C\left[7(\mathbf{h}/a)^2 - \tfrac{35}{4}(\mathbf{h}/a)^3 + \tfrac{7}{2}(\mathbf{h}/a)^5 - \tfrac{3}{4}(\mathbf{h}/a)^7\right] \quad \text{if } 0 \leq \mathbf{h} < a$$

(Geovariances, 2005)

2.3.3. Ordinary Kriging

One of the estimation methods that will be used for this project is ordinary kriging. Ordinary kriging is one of a set of estimation methods known as kriging and is a multiple linear regression technique based on local windows. For ordinary kriging it is assumed that the value $z(\mathbf{u}_i)$ of the attribute of interest at a sample location $\mathbf{u}_i$ is a value of the random variable $Z(\mathbf{u}_i)$ that describes the distribution of possible values at that location. The mean of $Z(\mathbf{u}_i)$ is denoted by $m(\mathbf{u}_i)$. The estimated value at an unsampled location **u** may be expressed in terms of random variables as:

$$z^*(\mathbf{u}) = m(\mathbf{u}) + \sum_{i=1}^{n(\mathbf{u})} \lambda_i(\mathbf{u})(Z(\mathbf{u}_i) - m(\mathbf{u}_i))$$

where $z^*(\mathbf{u})$ denotes the ordinary kriging estimate, $\lambda_i(\mathbf{u})$ denotes the kriging weight corresponding to sample i at location **u** and $n(\mathbf{u})$ is the number of sample locations that lie within the search window at **u** (Goovaerts, 1997). The values of the kriging weights are determined through the solution of the system of linear equations, called the ordinary kriging system, below:

$$\sum_{i=1}^{n(\mathbf{u})} \lambda_i(\mathbf{u}) C(\mathbf{u}_i - \mathbf{u}_k) + \mu(\mathbf{u}) = C(\mathbf{u} - \mathbf{u}_k)$$

$$\sum_{i=1}^{n(\mathbf{u})} \lambda_i(\mathbf{u}) = 1$$

where the function $C(\mathbf{h})$ refers to the covariance function of the attribute. The covariance function is related to the semivariogram of the attribute using the formula $C(\mathbf{h}) = C(0) - \gamma(\mathbf{h})$ where $C(0)$ denotes the variance of the attribute of interest.

2.3.4. Lognormal Ordinary Kriging

Another of the estimation methods that will be used for this project is lognormal ordinary kriging. This method is essentially a variation of the ordinary kriging estimation method and works particularly well for data that have a lognormal distribution. In many cases however the data distribution may be skewed but not really lognormal with the data approximately lognormal in the middle of the distribution but not at the tails. In these cases the lognormal distribution is still a better fit than the normal, though it is far from being perfect (Boufassa and Armstrong, 1989). Consequently, lognormal ordinary kriging can be expected to produce more reliable estimates than ordinary kriging.

For lognormal ordinary kriging, ordinary kriging is applied to the logarithms of the sample data. It is assumed that the value $z(\mathbf{u}_i)$ of the attribute of interest at a sample location $\mathbf{u}_i$ is a sample drawn from the random variable $Z(\mathbf{u}_i)$ that describes the distribution of possible values at this location. The lognormal variable $y(\mathbf{u}_i)$ is obtained from $z(\mathbf{u}_i)$ through the formula $y(\mathbf{u}_i) = \ln(z(\mathbf{u}_i) + c)$ where c is an additive constant. This additive constant is a shift applied to $z(\mathbf{u}_i)$ to assist in "normalising" the resulting distribution of $Y(\mathbf{u}_i)$, the corresponding random variable. The mean value of the lognormal data at the location $\mathbf{u}_i$ is given by $m(\mathbf{u}_i)$. The estimate for the natural logarithm of the value of the attribute of interest at an unsampled location $\mathbf{u}$ can be expressed as:

$$y^*(\mathbf{u}) = m(\mathbf{u}) + \sum_{i=1}^{n(\mathbf{u})} \lambda_i(\mathbf{u}_i)(y(\mathbf{u}_i) - m(\mathbf{u}_i))$$

where $y^*(\mathbf{u})$ and $\lambda_i(\mathbf{u})$ denote the kriging estimate and the kriging weight respectively corresponding to $\mathbf{u}_i$ at location $\mathbf{u}$ and $n(\mathbf{u})$ denotes the number of samples that lie within the search window at $\mathbf{u}$. The values of the kriging weights are determined through the solution of the associated ordinary kriging system.

The back-transformed estimates of the variable are then obtained from the logarithmic mean and variance using the conversion formulae:

$$z^*(\mathbf{u}) = \exp(y^*(\mathbf{u}) + \sigma_Y^2(\mathbf{u})/2 + \mu(\mathbf{u})) - c$$
$$\hat{\sigma}^2(\mathbf{u}) = \exp(\sigma_Y^2(\mathbf{u}))(1 + \exp(-(\sigma_Y^2(\mathbf{u}) + \mu(\mathbf{u})))(\exp(-\mu(\mathbf{u})) - 2)$$

where $\mu(\mathbf{u})$ is the Lagrange parameter that accounts for the constraint on the weights and $y^*(\mathbf{u})$ and σ_Y^2 are the kriging estimate and variance of the logarithmically transformed data respectively (Geovariances, 2005).

2.4. *Spatial Association*

In addition to the usual measures of correlation, measures of spatial association are also needed when analysing the relationship of two, or more, spatially defined variables. Correlation coefficients (such as Pearson's correlation and Spearman's rank order correlation) quantify the relationship between two variables without taking explicit account of the actual positions of the observations (Haining, 1987). Measures of spatial association however (such as Tjøstheim's index) expand on this by specifically including the physical position of the data when analysing the degree of association between two variables.

2.4.1. Tjøstheim's Index of Spatial Association

Tjøstheim's index of spatial association is a numerical measure of spatial correlation between variables that explicitly uses spatial information to help characterise the observed degree of correspondence (Hubert and Golledge, 1982). This index is used for two variables, F and G, observed over the same n locations to see if the position of the location ranked i for the first variable can be predicted by knowledge of the location with the same rank for the second variable. By computing the distance between each pair of identically ranked observations on the two variables the physical locations of the data are taken into account. To calculate Tjøstheim's Index the coordinates of the locations are first standardised such that:

$$\sum_{i=1}^{n} x_F(i) = \sum_{i=1}^{n} x_G(i) = \sum_{i=1}^{n} y_F(i) = \sum_{i=1}^{n} y_G(i) = 0$$

and

$$\frac{1}{n}\sum_{i=1}^{n} x_F^2(i) = \frac{1}{n}\sum_{i=1}^{n} x_G^2(i) = \frac{1}{n}\sum_{i=1}^{n} y_F^2(i) = \frac{1}{n}\sum_{i=1}^{n} y_G^2(i) = 1\,.$$

where $(x_F(i), y_F(i))$ and $(x_G(i), y_G(i))$ denote the location of rank i on F and G respectively. Tjøstheim's Index A is then calculated as:

$$A = \frac{\sum_{i=1}^{n}\left[x_F(i)x_G(i) + y_F(i)y_G(i)\right]}{\sum_{i=1}^{n}\left(x_i^2 + y_i^2\right)}$$

where any tied ranks are solved by ordering locations with equal rank firstly by ascending order of x and then ascending order of y.

Under randomization of ranks, the index has a normal distribution with E(A) = 0 and var(A) = $\frac{1 + r_{xy}^2}{2(n-1)}$, where r_{xy} is the Pearson correlation coefficient between the set of x and y coordinates over the n locations. The value for the test statistic used for testing the null hypothesis, that there is no spatial association between the variables F and G, is calculated as:

$$z = \frac{A}{\sqrt{\mathrm{var}(A)}}$$

with the null hypothesis being rejected at level of significance ∂ if $z > z_{\partial/2}$ or $z < -z_{\partial/2}$.

3. Data Sets

3.1. Data Preparation

3.1.1. Shark Bay Dedicated Scallop Fleet Logbook Data

The Shark Bay dedicated scallop (Class A) fleet keep detailed logbooks throughout the fishing season. The data collected in these logbooks for the 2000 to 2005 fishing seasons have been used in this thesis. The opening and closing dates for these seasons are displayed in Table 1. These logbooks consists of records for each trawl shot containing the vessel number, the date, the starting location (in longitude and latitude), the number of minutes spent fishing (effort) and the amount of scallops caught (in kilograms of meat weight).

Table 1: Opening and closing dates for the Shark Bay scallop fishing season, 2000-2005

Season	2000	2001	2002	2003	2004	2005
Open	3rd May	28th Apr	6th May	20th May	18th Mar	10th Mar
Close	4th Nov	28th Oct	28th Oct	1st Nov	25th Oct	13th Oct

The original data files were provided by the Department of Fisheries in Microsoft Excel format and a considerable amount of manipulation was performed on the data before analysis was carried out. Initially the data were screened and any records that were missing values for the shot location or shot duration were removed from the files. Observations that contained values that were clearly outliers, such as extremely short durations or excessively high catches, were also removed. Several modifications were then made to enhance the data and to prepare them for analysis. Firstly the shot locations were converted to longitude and latitude in nautical miles (LatNM and LongNM) relative to longitude 113° and latitude 24° S. This was achieved using the formulae:

$$LatNM = (latitude + 24) \times 60$$

$$LongNM = (longitude - 113) \times 60 \times \cos\left(\frac{latitude}{180\pi}\right).$$

Many vessels were recording catches aggregated over several trawl shots rather than logging the catch details after each shot individually. These aggregated records account for a large proportion of the total catch for each season (Bloom, et al., 2006). To ensure comparability the data were aggregated for each vessel over each day and the aggregate was located at the average (centroidal) location. These locations were calculated by weighting the coordinates of each shot of the day by its duration. The formulae used to calculate the average location are as follows:

$$\text{Long}(v) = \frac{\sum_{i=1}^{n_v} t_i^v long_i^v}{\sum_{i=1}^{n_v} t_i^v}, \qquad \text{Lat}(v) = \frac{\sum_{i=1}^{n_v} t_i^v lat_i^v}{\sum_{i=1}^{n_v} t_i^v}$$

where v denotes the vessel number, n_v the number of shots for vessel v, t_i^v the duration of the i[th] shot of vessel v, and $long_i^v$ and lat_i^v the corresponding longitude and latitude in nautical miles.

3.1.2. Shark Bay Prawn Fleet Logbook Data

The Shark Bay prawn and scallop (Class B) fleet keep similar logbooks to the dedicated scallop fleet. This thesis has also used the data from these logbooks for 2000 to 2005 fishing seasons. The opening and closing dates for these seasons are listed in Table 2. These logbooks consist of observations made on a shot-by-shot basis for each day of the fishing season. For each observation (trawl shot) the vessel number and date are recorded along with the shot number for that date, the starting location (in longitude and latitude) of the shot, the time spent fishing (in minutes) and the amount of prawns caught (in kilograms) by species. In addition to this, the amount of scallops caught (in kilograms of meat weight) is recorded for those shots where scallops were caught.

Table 2: Opening and closing dates for the Shark Bay prawn fishing Seasons, 2000 -2005

Season	2000	2001	2002	2003	2004	2005
Open	13th Mar	14th Mar	6th Mar	6th Mar	16th Mar	8th Mar
Close	4th Nov	28th Oct	28th Oct	1st Nov	25th Oct	13th Oct

The Class B fleet logbook data were also stored in Microsoft Excel format and manipulation, similar to that for the Class A fleet logbook data, was performed to prepare them for analysis. This included removing records that had missing location or duration values. Observations that were obviously outliers were also removed from the data set and the locations were converted to longitude and latitude in nautical miles relative to longitude 113° and latitude 24° S.

3.1.3. Moving Window Statistics

Moving window statistics were calculated for the Class A and Class B fleet logbook data to allow them to be compared with variables from other data sets. Moving windows consist of rectangular parts of the data area in which univariate statistics can be calculated. These windows form a rectangular grid over the study region with the windows either overlapping or not. In this thesis moving window statistics have been calculated for each fishing season using a 1x1 nautical mile grid with non-overlapping windows. The values for these moving window statistics were assigned to the corresponding nodes for each window and have been treated as grided data.

For the Class A fleet data two specific moving window statistics have been studied. The first is the total scallop catch, calculated as the sum of the catch data located within each window, and the second is the overall scallop catch rate, computed as the total scallop catch divided by the sum of the fishing effort within each window.

Moving window statistics were also calculated for the fishing effort used by the Class B fleet. Two of these statistics have been investigated in this thesis with the first being the total fishing effort, computed as the sum of the effort data located within each window, and the pre-season total effort, defined as the sum of the effort recorded before the start of the scallop fishing season within each window.

In addition to the moving window statistics calculated for the data of each individual fleet, moving window statistics were computed using the fishing effort and scallop catch data for the two fleets combined. In particular, the total scallop catch for the Class A and Class B fleets combined and the overall catch rate for both fleets combined are investigated in this project.

3.1.4. Scallop Recruitment Survey Data

In November or December of each year the Department of Fisheries carries out a recruitment survey in the Shark Bay Scallop Fishery. This thesis has used the results from the 1999 to 2005 surveys. These surveys consist of observations recorded by shot containing information on the date, the start and end locations of each shot, the duration and distance of the shot, the trawl speed and the number of recruit (size < 76mm) and residual (size > 76mm) scallops caught. In addition to this, any prawn catches are recorded as are environmental conditions such as water temperature and cloud cover. The results of the survey are used by the Department of Fisheries to determine the abundance of recruit and residual scallops, which permits the setting of the opening date of the scallop fishery and an estimation of the total scallop catch for the following season.

The number of recruits and the total number of scallops caught were calculated for each shot of the survey and assigned to the coordinates located at the mid-point of the start and end locations of the relevant shot. As the trawling speed affects the efficiency of the trawl equipment the recruit and total scallop catch values were standardised to the equivalent catch at a speed of 3.4 knots using the formula:

$$c_{st} = \frac{c}{3.2331 - 0.6485v}$$

with v denoting the trawl speed in knots and c and c_{st} the catch and standardised catch respectively. The standardised recruit and total scallop catch values were then converted to a density taking into account the distance trawled, the number of nets and the width of the nets using the formula:

$$d = \frac{c_{st}}{2tw}$$

where T and w denote the shot distance and the width per net in nautical miles, assuming a width of six-fathoms of the head ropes for the two nets (Mueller et al., 2004).

3.2. Exploratory Data Analysis

3.2.1. Shark Bay Dedicated Scallop Fleet Logbook Data

Summary statistics of the total scallop catch for the Shark Bay North (consisting of the Red Cliff and NW Peron fishing grounds displayed in Figure 2) and Denham Sound regions are displayed in Table 3 and Table 4. These show that for most fishing seasons in Shark Bay North over 100 of the 1x1 nautical mile windows contained some data with just 11 and 32 windows with recorded data for the 2003 and 2005 seasons respectively. The minimum total catch was typically below 20 kg except in the 2004 season which had a minium total catch of 113 kg. The maximum and mean total catch values display considerable variability between seasons as does the standard deviation. For each season the coefficient of variation is close to 1 with the exception for 2004 which has a much larger coefficient of variation. For every season, except 2002, the coefficient of skewness has a moderate to strong positive value.

Table 3: Summary statistics for 1x1 nautical mile windows, Class A fleet total scallop catch (kg), Shark Bay North

SB North	2000	2001	2002	2003	2004	2005
Count	118	161	281	11	141	32
Minimum	0.00	18.00	0.00	12.00	113.00	10.00
Maximum	5117.00	2737.00	8966.00	3720.00	3356.00	1967.00
Mean	1278.07	468.65	645.04	1470.09	656.62	370.16
Std. Dev.	1253.55	505.76	1083.32	1399.22	612.31	363.33
Variat.Coef.	0.98	1.08	1.68	0.95	0.93	0.98
Skewness	1.33	2.23	3.86	0.37	2.22	2.75

The summary statistics for Denham Sound indicate that this region has relatively few total catch data, compared to the Shark Bay North region, except for 2005 season which has a count of 110. Both the minimum and maximum values vary substantially between seasons with the largest maximum value recorded for the 2003 season (4,922 kg). There appears to be an increasing trend in the mean total catch value for Denham Sound with the highest mean recorded for the 2005 season (1,649.11 kg). For each season, except 2000, the coefficient of skewness is (moderate to strong) positive.

Table 4: Summary statistics for 1x1 nautical mile windows, Class A fleet total scallop catch, Denham Sound

Denham Sound	2000	2001	2002	2003	2004	2005
Count	2	23	66	27	62	110
Minimum	192.00	36.00	24.23	150.00	216.00	168.00
Maximum	828.00	948.00	4713.00	4922.00	5188.00	9887.00
Mean	510.00	363.30	1088.37	1493.70	1400.84	1649.11
Std. Dev.	318.00	269.88	985.47	1263.47	1032.78	1633.08
Variat.Coef.	0.62	0.74	0.91	0.85	0.74	0.99
Skewness	0.00	0.74	1.81	1.28	1.52	2.23

Histograms of the Class A fleet total catch data, with fitted theoretical normal distribution curves, are displayed in Figure 3 and Figure 4 for the Shark Bay North and Denham Sound regions respectively. These show that in almost every case the data have a considerable positive skew with several outliers often located at the upper tail of the distribution.

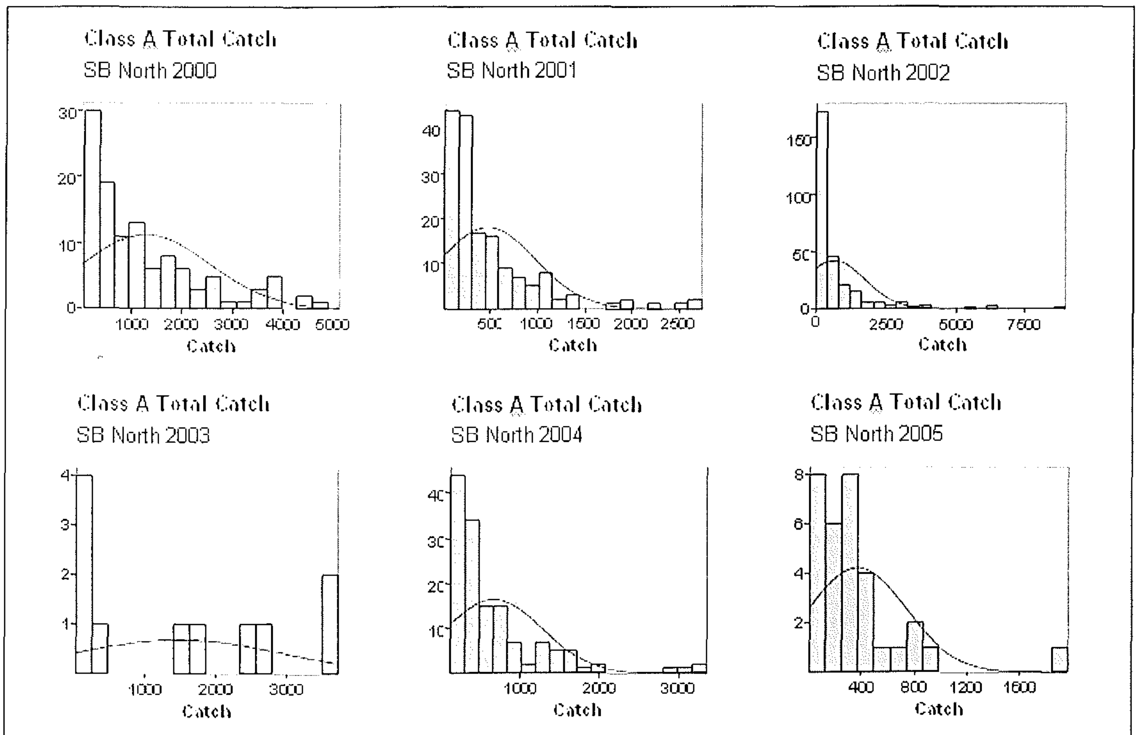

Figure 3: Histograms, Class A Fleet Total Catch, Shark Bay North

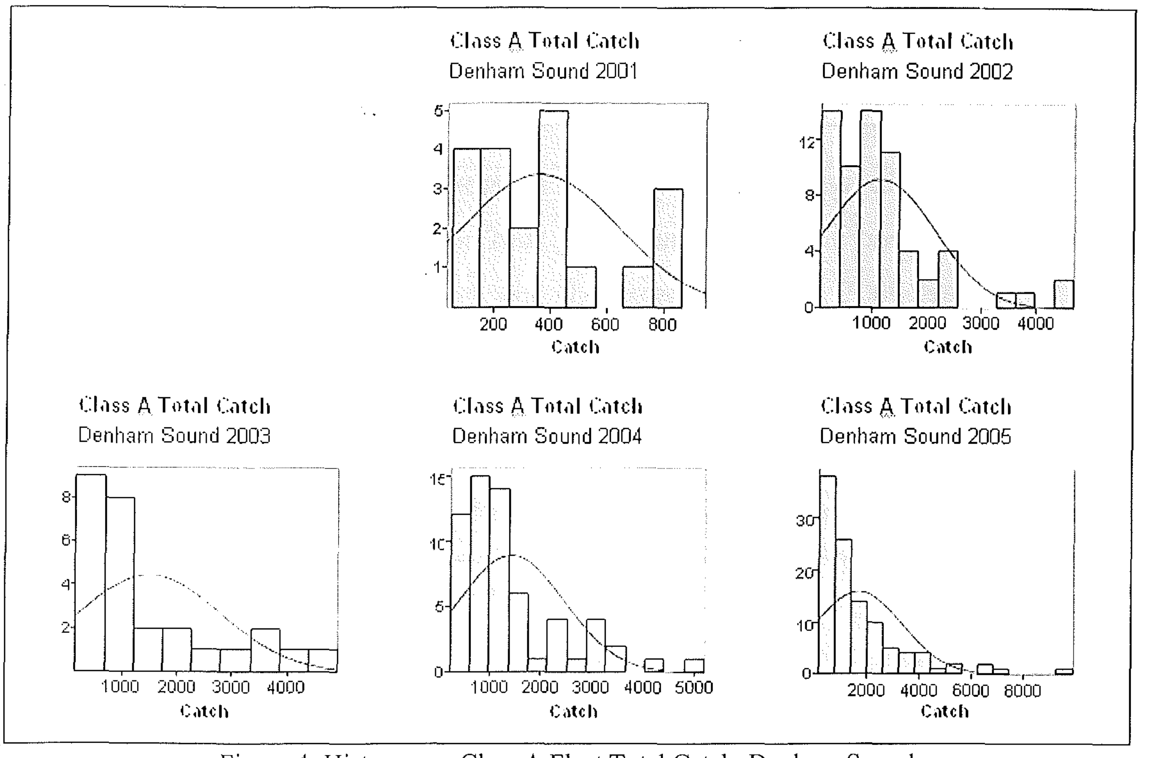

Figure 4: Histograms, Class A Fleet Total Catch, Denham Sound

Summary statistics of the overall catch rate for the Shark Bay North region are presented in Table 5 and for Denham Sound in Table 6. These show that for the Shark Bay North region the maximum and mean catch rates vary considerably between seasons with the highest mean catch rate recorded for the 2003 season (36.44 kg/hr). For every season except 2002 the coefficient of variation is less than 1 and the coefficient of skewness is (moderate to strong) positive for each season.

Table 5: Summary statistics for 1x1 nautical mile windows, Class A fleet scallop catch rate (kg/hr), Shark Bay North

SB North	2000	2001	2002	2003	2004	2005
Count	118	161	281	11	141	32
Minimum	0.00	1.95	0.00	2.25	6.32	8.00
Maximum	49.14	74.27	221.93	90.98	96.43	46.67
Mean	18.36	14.02	20.07	36.44	20.44	20.60
Std. Dev.	10.39	9.23	22.85	27.33	12.98	8.44
Variat.Coef.	0.57	0.66	1.14	0.75	0.63	0.41
Skewness	0.79	2.90	4.37	0.41	2.36	0.90

For Denham Sound the highest minimum, maximum and mean values were recorded for the 2003 fishing season. These statistics also show that the standard deviations are somewhat comparable between seasons with the coefficients of variation varying between 0.26 for 2005 and 0.58 for 2002. A moderate to strong positive coefficient of skewness is given for every season with the exception of the 2000 season for which there are only 2 catch rate values.

Table 6: Summary statistics for 1x1 nautical mile windows, Class A fleet scallop catch rate (kg/hr), Denham Sound

Denham Sound	2000	2001	2002	2003	2004	2005
Count	2	23	66	27	62	110
Minimum	13.09	5.33	2.27	16.07	11.62	14.50
Maximum	37.92	44.38	60.00	115.71	90.15	86.40
Mean	25.51	17.28	31.19	56.73	40.19	43.51
Std. Dev.	12.42	10.00	11.33	26.43	17.52	11.17
Variat.Coef.	0.49	0.58	0.36	0.47	0.44	0.26
Skewness	0.00	1.20	0.43	0.77	0.87	0.48

Histograms of the overall scallop catch rate are displayed for each region and season in Figure 5 and Figure 6. These show that the distributions for the Shark Bay North region typically have quite strong positive skews except for the 2000 season which has a weak positive skew. The distributions for Denham Sound however only have weak positive skews with the data for 2005 appearing to have an approximately normal distribution.

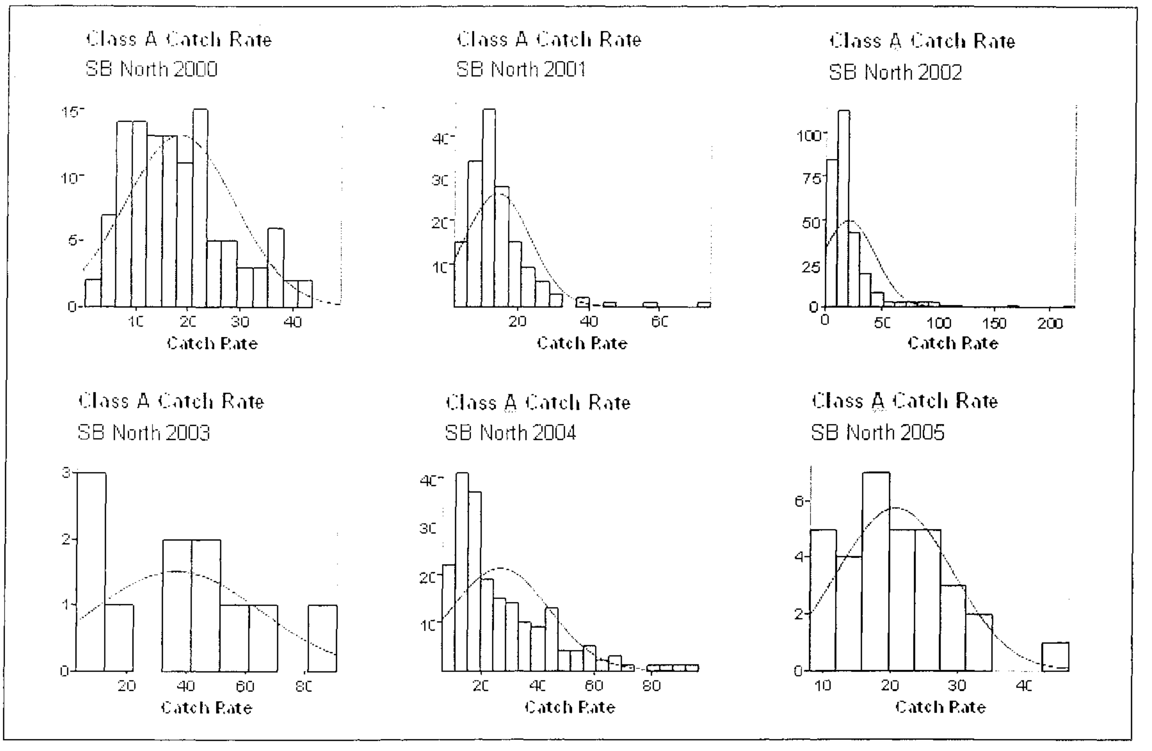

Figure 5: Histograms, Class A fleet catch rate, Shark Bay North

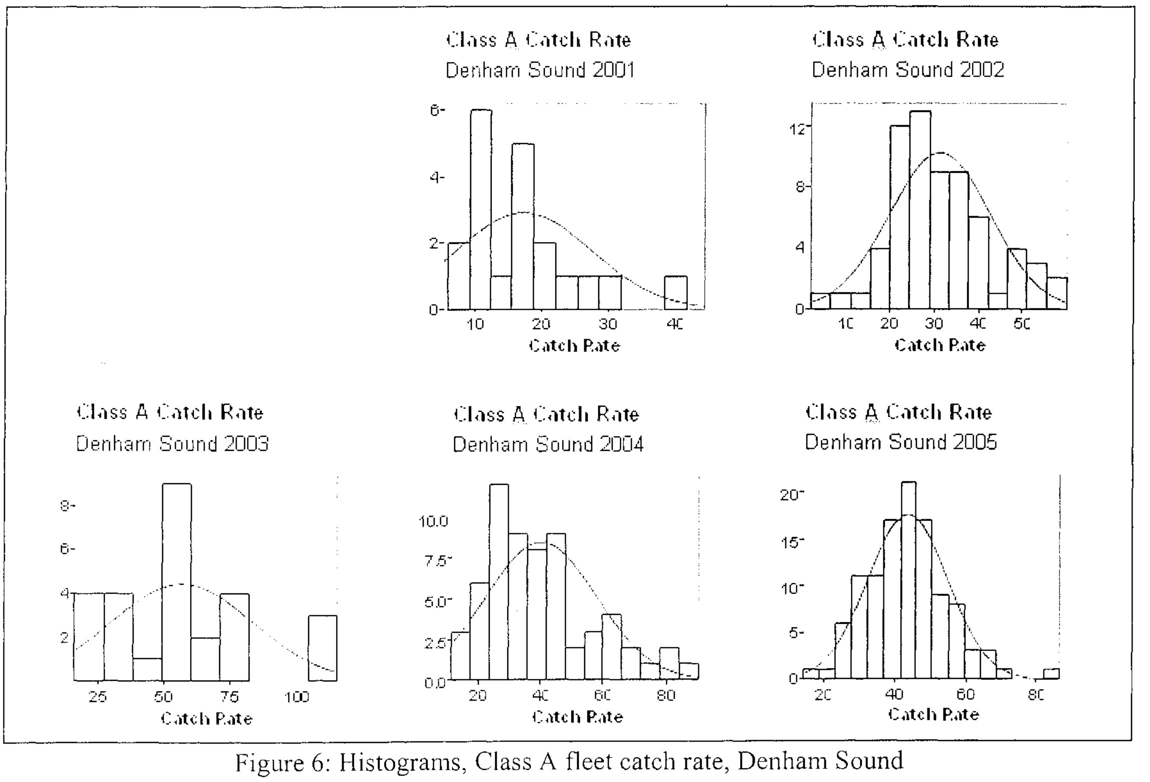

Figure 6: Histograms, Class A fleet catch rate, Denham Sound

3.2.2. Shark Bay Prawn Fleet Logbook Data

Summary statistics for the total fishing effort are presented for each region in Table 7 and Table 8. For the Shark Bay North region these show that the count for each season is generally between 500 and 600. The summary statistics also reveal that the minimum and maximum total effort values vary substantially between seasons. The mean total effort values for the 2000 to 2003 seasons are similar however they decline considerably in the 2004 and 2005 seasons. Although the standard deviation values vary substantially across seasons all the coefficients of variation are less than 1. Finally, for each season the total effort data have a moderate to high positive coefficient of skewness.

Table 7: Summary statistics for 1x1 nautical mile windows, Class B fleet total fishing effort (mins), Shark Bay North

SB North	2000	2001	2002	2003	2004	2005
Count	464	547	559	533	556	514
Minimum	145.00	295.00	20.00	290.00	240.00	210.00
Maximum	13850.00	17600.00	17250.00	22560.00	19275.00	16550.00
Mean	3851.59	3822.77	3813.27	3774.92	3363.69	2812.20
Std. Dev.	2975.20	2985.18	3278.01	3444.97	2802.12	2310.04
Variat.Coef.	0.77	0.78	0.86	0.91	0.83	0.82
Skewness	0.92	1.07	1.34	1.71	1.71	1.39

The summary statistics for Denham Sound reveal that there is a declining trend in the number of 1x1 nautical mile windows in which effort values were recorded. The mean total effort values for the 2000 to 2003 seasons are between 2,500 and 3,500 minutes while the means for the 2004 and 2005 seasons are above 3,500 minutes. The standard deviation values vary notably between seasons with the corresponding coefficients of variation all equal to or less than 1. For each season the total effort values have a low positive coefficient of skewness.

Table 8: Summary statistics for 1x1 nautical mile windows, Class B fleet total fishing effort (mins), Denham Sound

Denham Sound	2000	2001	2002	2003	2004	2005
Count	251	228	197	194	150	161
Minimum	240.00	150.00	360.00	350.00	135.00	150.00
Maximum	10390.00	23285.00	13675.00	10725.00	20945.00	13907.00
Mean	2690.64	3190.88	3221.60	2704.78	3916.84	3523.14
Std. Dev.	2243.73	3183.19	2553.19	2225.08	3703.68	2825.72
Variat.Coef.	0.83	1.00	0.79	0.82	0.95	0.80
Skewness	0.99	2.06	1.18	1.44	1.67	0.99

Histograms of the total fishing effort data are displayed for the Shark Bay North region in Figure 7 and for Denham Sound in Figure 8. These show that in each case the distribution of the total effort data has a considerably strong positive skew. In addition to this the histograms identify several possible outliers located at the upper tails of the distributions.

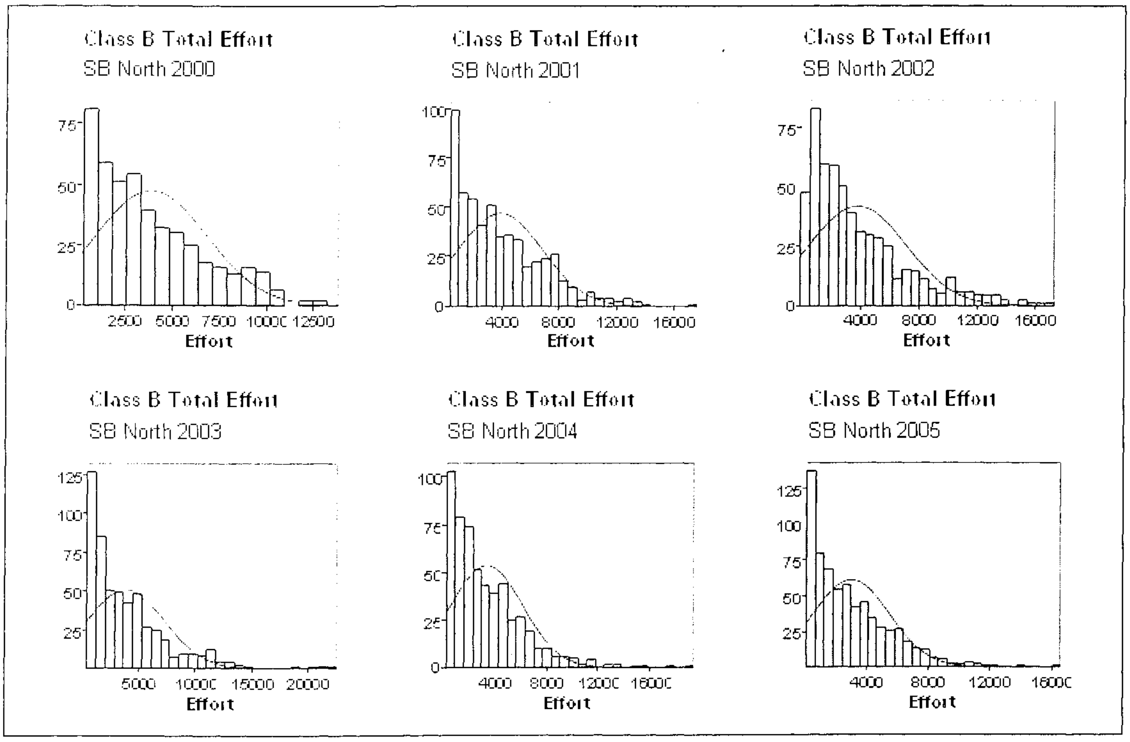

Figure 7: Histograms, Class B fleet total fishing effort, Shark Bay North

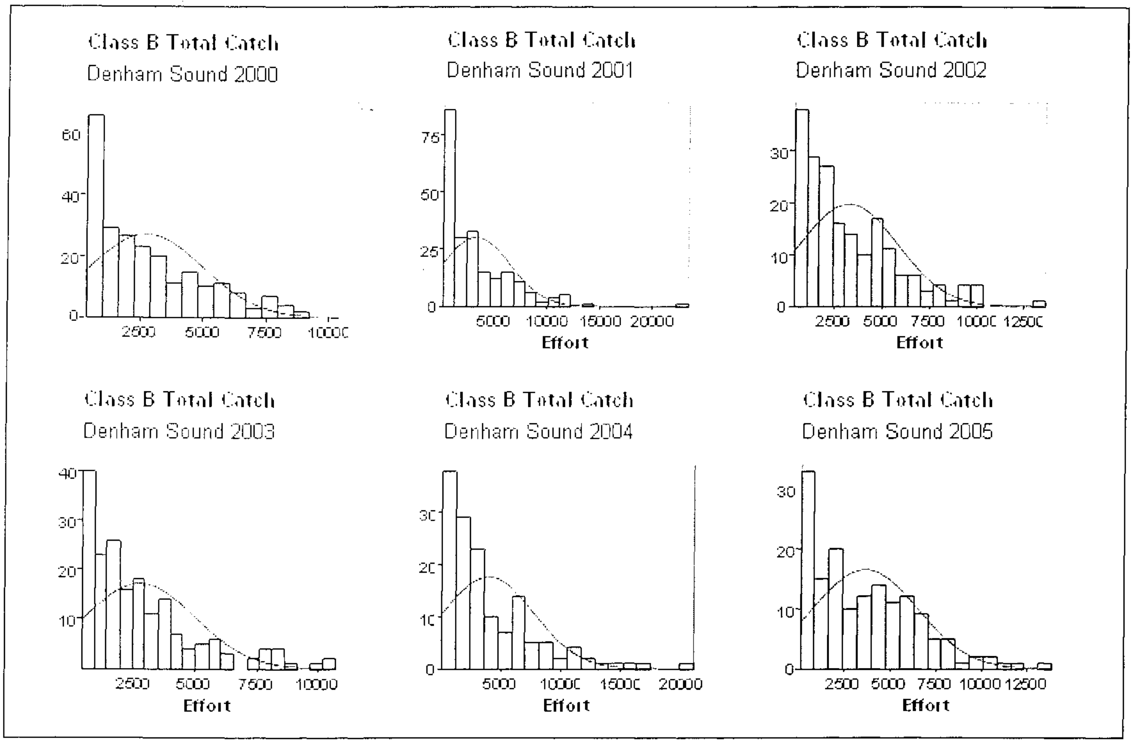

Figure 8: Histograms, Class B fleet total fishing effort, Denham Sound

Summary statistics for the pre-season total fishing effort of the Class B fleet are displayed for each region in Table 9 and Table 10. These show that for Shark Bay North the number of pre-season total effort values decreases markedly in the 2004 and 2005 fishing seasons. The means and standard deviations of the pre-season total effort values vary considerably between seasons with the coefficients of variation typically close to 1. For each season the data have a strong positive skew as indicated by the coefficient of skewness.

Table 9: Summary statistics for 1x1 nautical mile windows, Class B fleet pre-season total fishing effort (mins), Shark Bay North

SB North	2000	2001	2002	2003	2004	2005
Count	257	320	403	412	193	233
Minimum	270.00	210.00	435.00	315.00	60.00	110.00
Maximum	10188.00	13570.00	15310.00	18395.00	13515.00	8493.75
Mean	1968.09	1837.92	2353.12	2506.82	1778.12	1380.16
Std. Dev.	1874.86	1619.27	2322.97	2475.73	2102.18	1304.58
Variat.Coef.	0.95	0.88	0.99	0.99	1.18	0.95
Skewness	1.74	2.33	2.55	2.81	2.67	2.41

For Denham Sound the number of Class B pre-season total effort values differs markedly between seasons with no values present in the 2004 and 2005 seasons as the prawn fishery was not opened before scallop fishing commenced. The 2002 season has the highest mean value (1260.69 mins) while the 2001 season has the largest standard deviation (805.51 mins). For the 2000 to 2003 seasons the data have a low to moderate positive coefficient of skewness.

Table 10: Summary statistics for 1x1 nautical mile windows, Class B fleet pre-season total fishing effort, Denham Sound

Denham Sound	2000	2001	2002	2003	2004	2005
Count	12	79	51	43	-	-
Minimum	420.00	150.00	495.00	425.00	-	-
Maximum	1245.00	3905.00	3200.00	3460.00	-	-
Mean	642.50	1099.18	1260.69	968.60	-	-
Std. Dev.	193.55	805.51	705.28	610.72	-	-
Variat.Coef.	0.30	0.73	0.56	0.63	-	-
Skewness	2.36	1.58	0.77	1.96	-	-

Histograms of the pre-season total effort data are displayed for each region in Figure 9 and Figure 10. These show that in each case the data have a fairly strong positive skew. In addition to this a number of likely outliers are identified at the upper tails of the distributions.

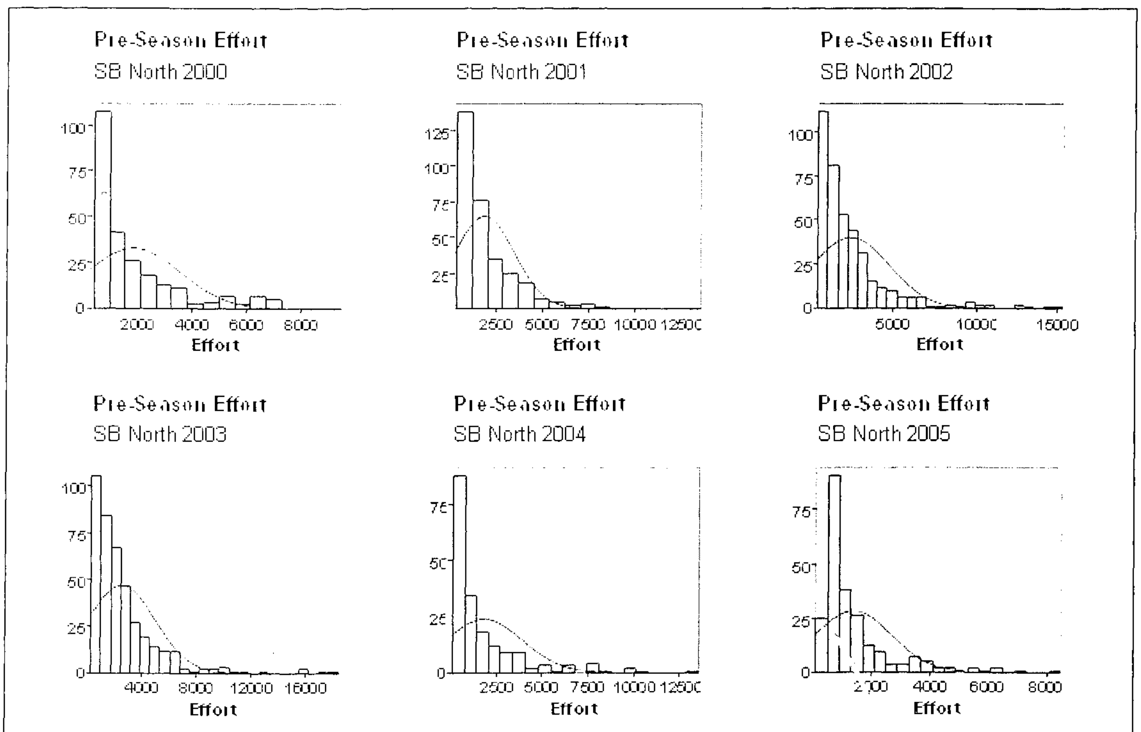

Figure 9: Histograms, Class B fleet pre-season total fishing effort, Shark Bay North

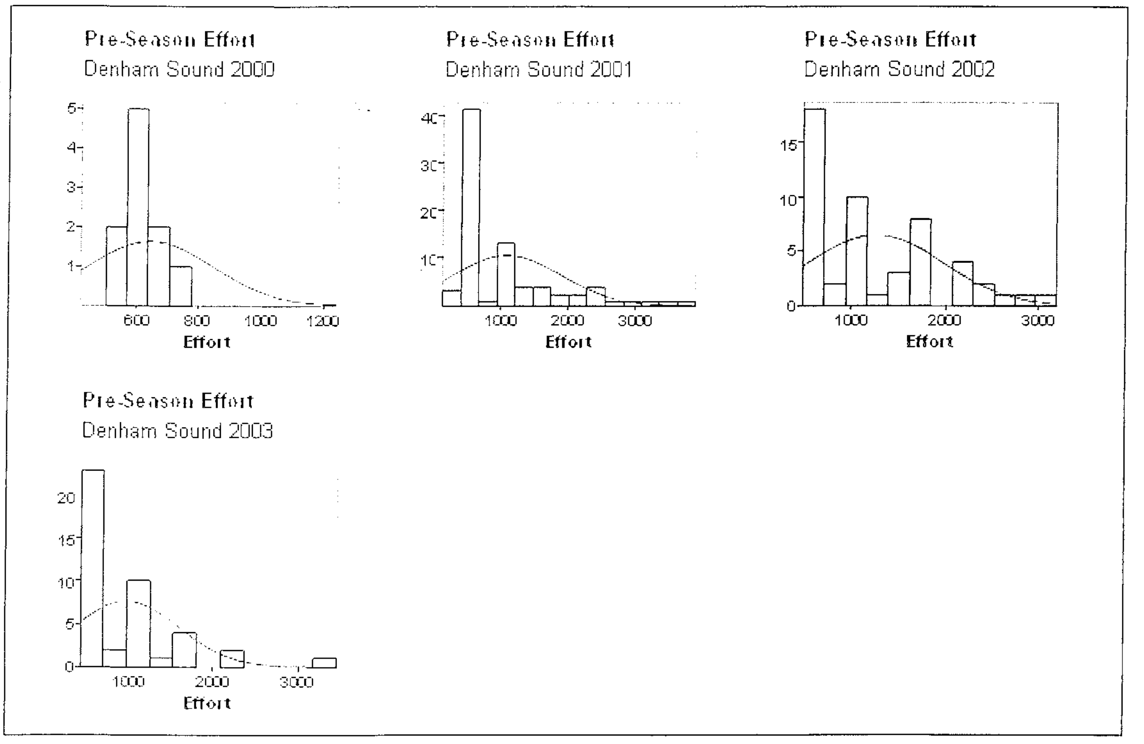

Figure 10: Histograms, Class B fleet pre-season total fishing effort, Denham Sound

3.2.3. Combined Shark Bay Prawn and Scallop Fleet Logbook Data

Summary statistics of the combined total scallop catch for the Shark Bay North region are presented in Table 11. These show that the number of combined total scallop catch values varies substantially between seasons. These statistics also reveal that the mean values fluctuate markedly between seasons. The standard deviations also differ considerably across seasons with each of the coefficients of variation greater than 1. For each season there is a high positive coefficient of skewness.

Table 11: Summary statistics for 1x1 nautical mile windows, combined Class A and B fleet total scallop catch, Shark Bay North

SB North	2000	2001	2002	2003	2004	2005
Count	279	393	333	172	336	328
Minimum	0.00	5.45	0.00	3.30	9.19	6.00
Maximum	5117.00	3401.04	8966.00	4020.60	3356.00	1967.00
Mean	590.72	350.17	588.25	187.24	371.60	208.33
Std. Dev.	1007.65	505.03	1013.63	422.76	523.33	247.41
Variat.Coef.	1.71	1.44	1.72	2.26	1.41	1.19
Skewness	2.48	3.10	4.13	5.96	2.72	2.40

Summary statistics of the total scallop catch of the combined Class A and Class B fleets in Denham Sound (Table 12) reveal that there is an increasing trend in the number of windows containing data for each season. In addition to this the minimum and maximum total catch values also exhibit an increasing trend as do the means and standard deviations. For each season the coefficient of variation is greater than 1 with a very high coefficient (3.10) for the 2000 season. The coefficient of skewness is positive for every case with a very large coefficient (7.18) for the 2000 season.

Table 12: Summary statistics for 1x1 nautical mile windows, combined Class A and B fleet total scallop catch, Denham Sound

Denham Sound	2000	2001	2002	2003	2004	2005
Count	64	145	156	174	158	174
Minimum	1.00	3.27	8.87	11.12	11.70	24.00
Maximum	828.00	1214.09	4713.00	4952.65	7231.52	12306.00
Mean	33.30	124.97	530.09	465.69	878.08	1496.66
Std. Dev.	103.22	200.87	837.61	768.70	1129.25	1758.32
Variat.Coef.	3.10	1.61	1.58	1.65	1.29	1.17
Skewness	7.18	3.21	2.58	3.57	2.29	2.92

Histograms of the combined total scallop catch data are displayed in Figure 11 and Figure 12. For each case, these histograms illustrate the moderate to strong positive skew of the data. In addition to this outlying values are identified at the upper tails of the distributions.

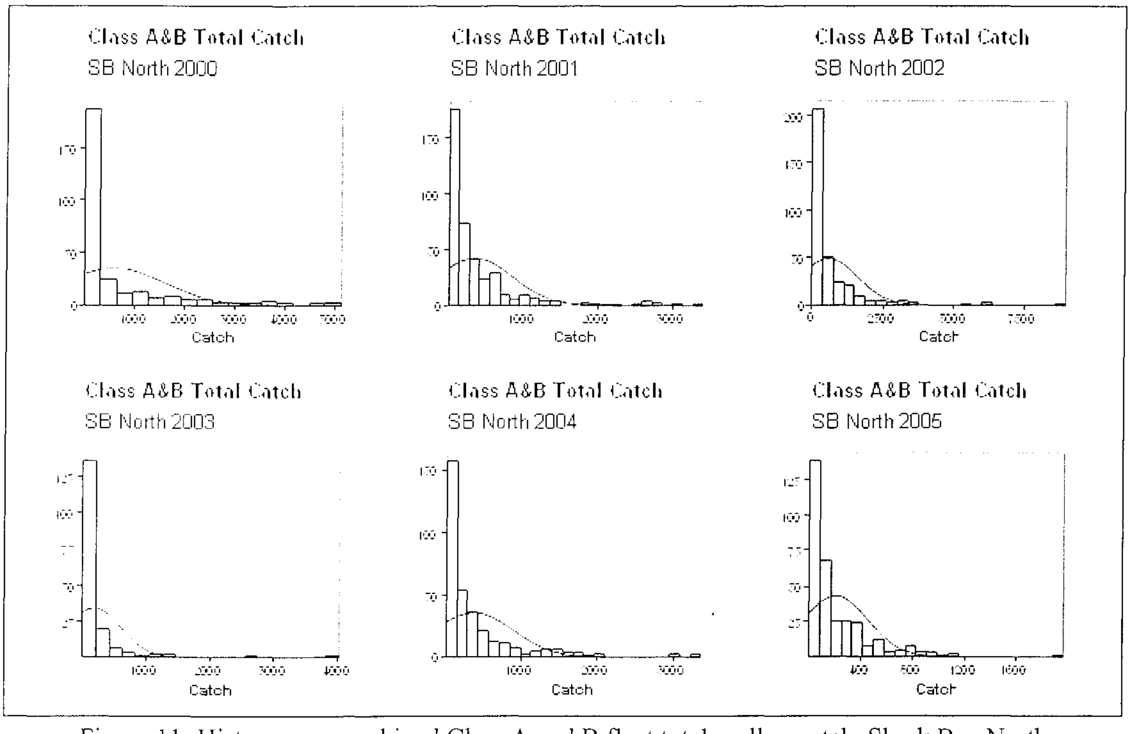

Figure 11: Histograms, combined Class A and B fleet total scallop catch, Shark Bay North

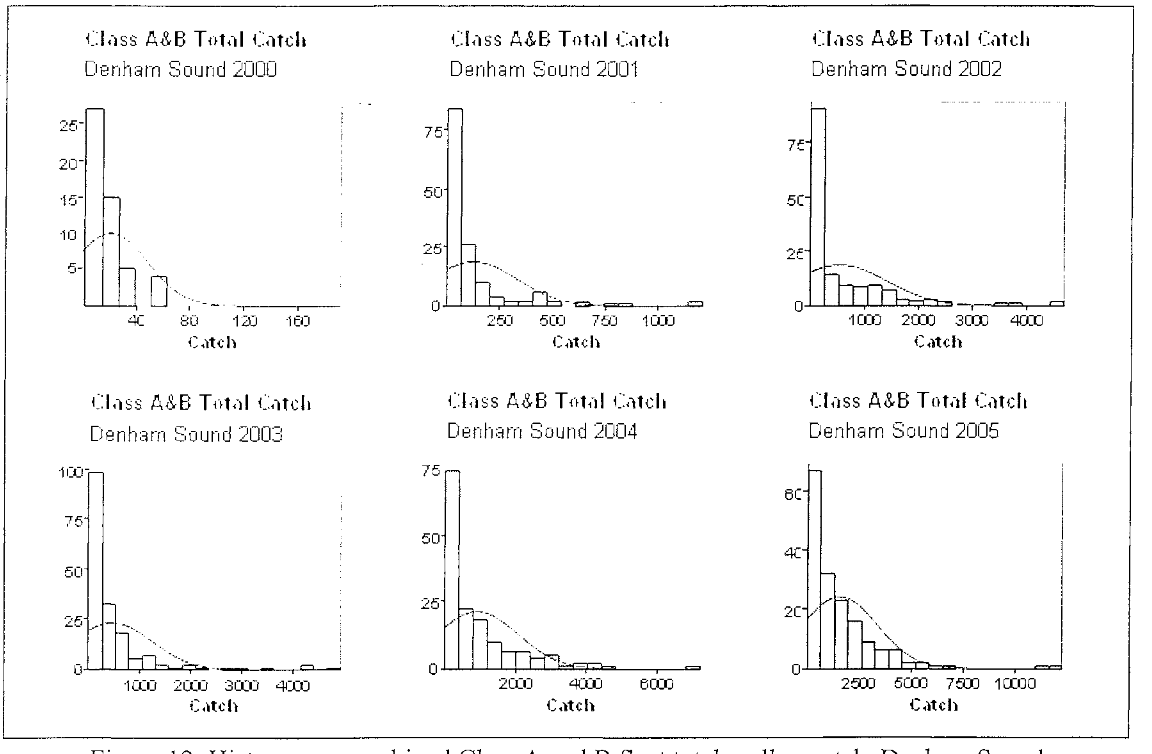

Figure 12: Histograms, combined Class A and B fleet total scallop catch, Denham Sound

3.2.4. Scallop Recruitment Survey Data

Summary statistics of the total scallop density for each region are presented in Table 13 and Table 14. These show that for the Shark Bay North region the minimum and maximum values vary considerably between years. The highest mean value (22,853.3 scallops/nmil^2) was recorded in the 2003 survey with the lowest mean (11,336.9 scallops/nmil^2) recorded in the 2004 season. Both the standard deviation and coefficients of variation vary substantially between years. For each year the data have a weak to strong positive skew as indicated by the coefficient of skewness.

Table 13: Summary statistics, total scallop density (scallops/nmil^2), Shark Bay North

SB North	1999	2000	2001	2002	2003	2004	2005
Count	46	42	30	45	47	47	47
Minimum	0.0	0.0	589.6	142.0	351.0	0.0	724.0
Maximum	177793.0	68060.1	42674.1	203626.0	125440.0	33150.3	37229.3
Mean	19976.9	12758.1	13461.3	16534.4	22853.3	11336.9	14086.2
Std. Dev.	36844.1	14524.4	11443.6	32973.0	27344.0	8774.6	10069.8
Variat.Coef.	1.8	1.1	0.9	2.0	1.2	0.8	0.7
Skewness	3.1	2.2	1.1	4.5	1.9	0.9	0.5

The summary statistics for Denham Sound indicate a change of survey design with the number of locations sampled increasing in later years. In addition to this the summary statistics reveal an increasing trend in both the maximum and mean total scallop density values. The standard deviation values also exhibit an increasing trend however the coefficients of variation do not. For each survey the coefficient of skewness has a low to moderate positive value.

Table 14: Summary statistics, total scallop density (scallops/nmil^2), Denham Sound

Denham Sound	1999	2000	2001	2002	2003	2004	2005
Count	16	10	13	26	25	28	45
Minimum	0.0	0.0	447.1	0.0	2482.3	2949.2	134.0
Maximum	5230.0	18349.9	24818.3	74543.2	196617.5	138535.7	241102.2
Mean	1279.5	5085.0	7483.3	9261.1	33235.6	30533.8	36033.1
Std. Dev.	1576.5	5819.1	7651.1	18111.2	44349.7	31811.8	42883.5
Variat.Coef.	1.2	1.1	1.0	2.0	1.3	1.0	1.2
Skewness	1.9	1.4	1.4	3.1	2.8	2.0	3.0

Histograms of the total scallop density data for the Shark Bay North region are displayed by year in Figure 13. These illustrate that the strength of the positive skew of the corresponding distributions vary markedly between years. The histograms also identify outlying values in the 1999, 2000, 2002 and 2003 surveys at the upper tails of the distributions.

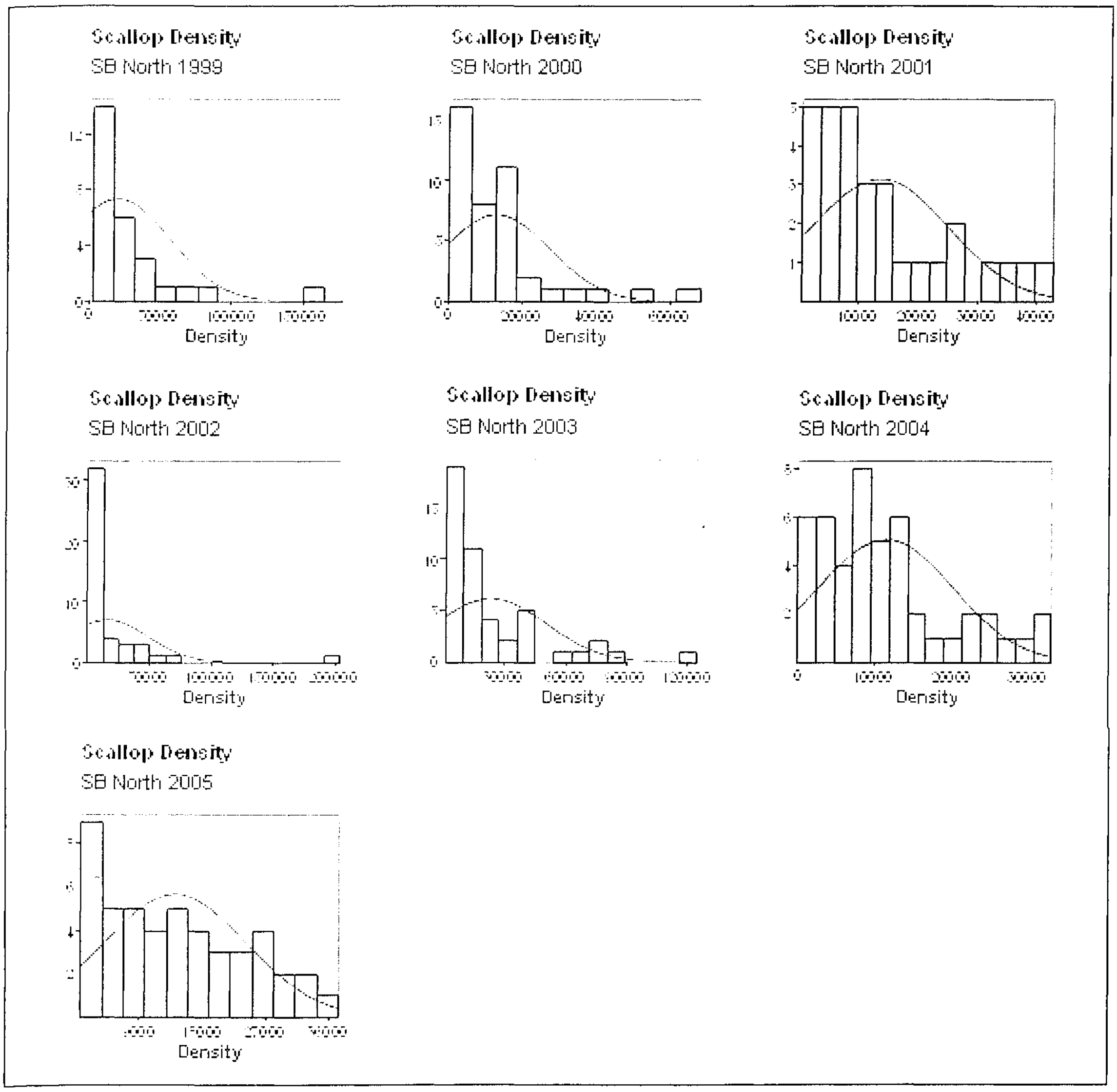

Figure 13: Histograms, total scallop density, Shark Bay North

Histograms of the total scallop density for Denham Sound are presented in Figure 14. These display the positive skew present in the data for each survey. In addition to this the histograms identify outlying values at the upper tails of the distributions for each survey.

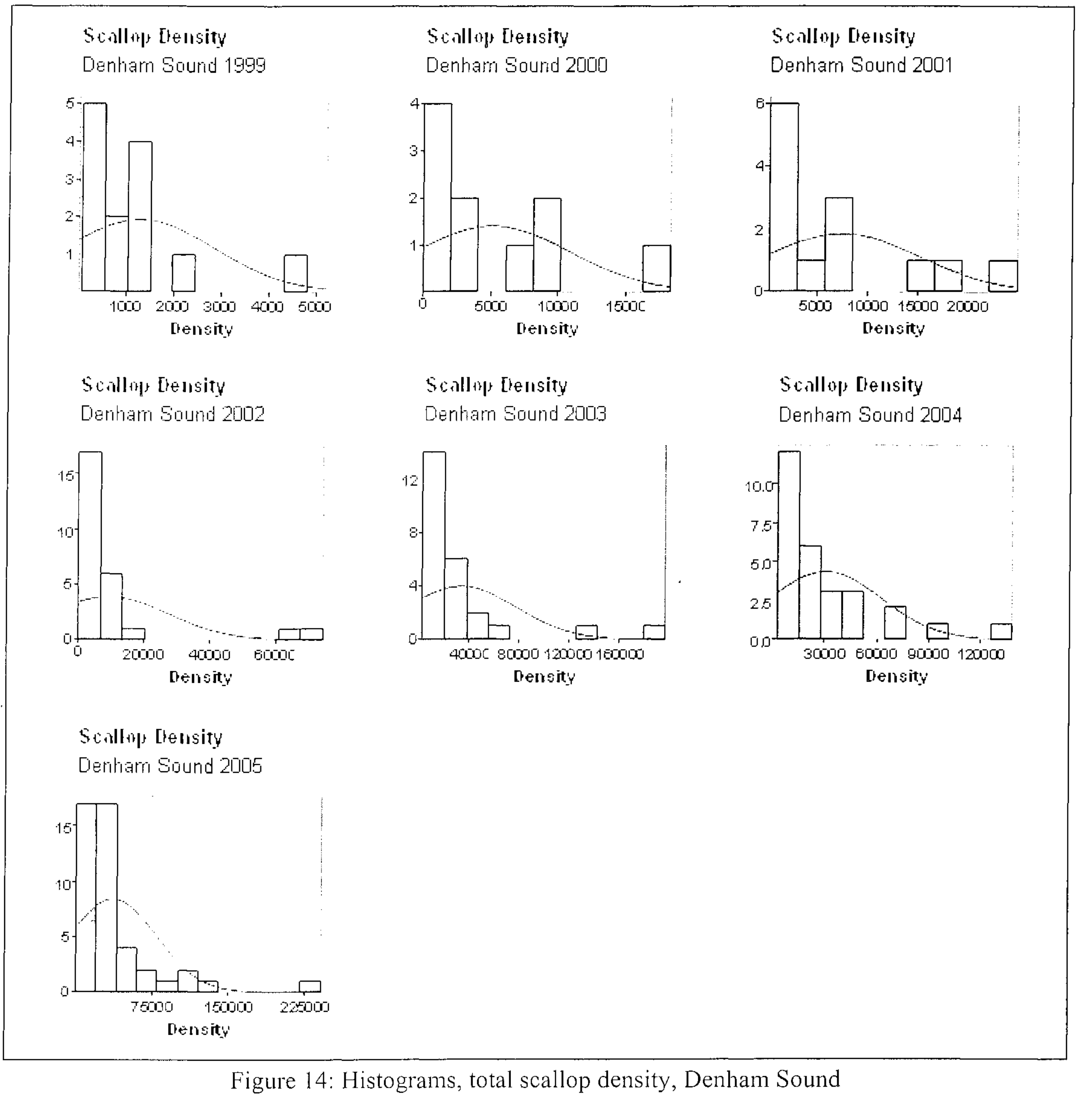

Figure 14: Histograms, total scallop density, Denham Sound

Summary statistics of the recruit scallop density in the Shark Bay North region for the 1999 to 2005 surveys are displayed in Table 15. These show that for each survey, except 2000, the minimum recruit density was zero while the maximum recruit density varies considerably between surveys. The mean value also differ substantially between surveys with the 1999 survey recording the highest recruit density (18,788.1). The standard deviation values vary notably with the coefficients of variation are between 1.1 and 1.5 for most seasons. There is a strong skew in the recruit density data for each survey as indicated by the coefficient of skewness.

Table 15: Summary statistics, recruit scallop density (scallops/nmil^2) Shark Bay North

SB North	1999	2000	2001	2002	2003	2004	2005
Count	46	42	30	45	47	47	47
Minimum	0.0	0.0	143.0	0.0	0.0	0.0	0.0
Maximum	173215.0	55346.5	14564.4	63452.0	86738.9	16152.2	27646.2
Mean	18788.1	9217.3	3056.9	10686.9	16358.0	2929.2	5840.1
Std. Dev.	35923.1	10540.8	3232.4	15620.0	20247.8	3874.3	6988.2
Variat.Coef.	1.9	1.1	1.1	1.5	1.2	1.3	1.2
Skewness	3.0	2.3	1.9	2.0	1.7	1.8	1.6

Histograms of the recruit scallop density for Shark Bay North are given in Figure 15. These illustrate the strong positive skew present in the data for each survey. For every survey the histograms also display several outlying values at the upper tail of the distributions.

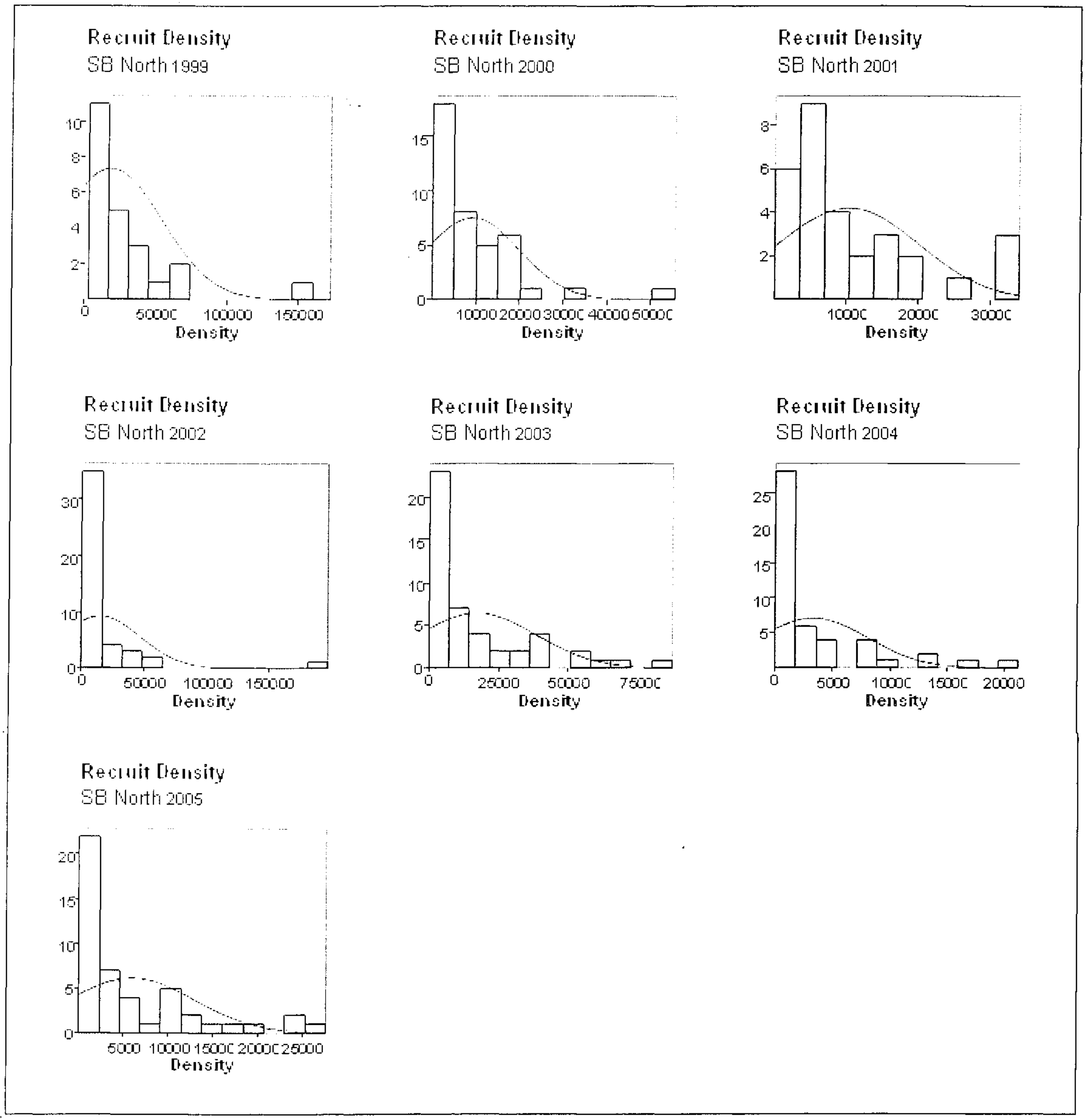

Figure 15: Histograms, recruit scallop density, Shark Bay North

4. Analysis

4.1. Spatial Maps

4.1.1. Scallop Survey Densities and Lognormal Ordinary Kriging Estimates

Estimates were calculated for the scallop survey total density data in order to assess the spatial association between the survey densities and the fishing effort and scallop catch for the following seasons. As the distributions of the survey data were positively skewed, lognormal ordinary kriging (described in Section 2.3.4.) was used to calculate the estimates. The additive constants, semivariogram models and search window parameters from Mueller et al. (2004) and Bloom et al. (2006) were used in the estimation. They are summarised in Table 16, Table 17 and Table 18.

Table 16: Constants added to scallop density survey data

Region	1999	2000	2001	2002	2003	2004	2005
SB North	135	2000	1	0	0	1100	3500
Denham	135	2000	1	100	0	0	300

Omnidirectional semivariograms were constructed for the Shark Bay North region as these data sets have elongated study regions with an insufficient number of data pairs in the east-west direction to allow for the calculation of directional semivariograms. The semivariograms for Denham Sound were also omnidirectional as the continuity between pairs of the corresponding data does not differ substantially between directions. The corresponding models for these experimental semivariograms each consist of a nugget and a single isotropic spherical structure, except the model for the Shark Bay North region in 2002 which had two spherical structures. The parameters for these semivariogram models are given in Table 17 and Table 18. In each case the ranges of the Denham Sound models are somewhat shorter than the corresponding Shark Bay North region models. For the Shark Bay North region, the model for 1999 has a considerably higher sill than the other models while for Denham Sound the 2002 model has the greatest sill which is indicative of the higher degree of variability present in the corresponding data. For both regions, the models for 1999 and 2002 have substantially longer ranges than the other models indicating greater spatial correlation.

Table 17: Log(Total Density) semivariogram parameters, Shark Bay North region

	1999	2000	2001	2002	2003	2004	2005
Nugget	0.50	0.40	0.28	0.36	0.70	0.40	0.23
Structure$_1$	Spherical	Spherical	Spherical	Spherical	Spherical	Spherical	Spherical
Sill$_1$	3.23	0.42	0.80	0.92	0.95	0.27	0.19
Range$_1$	9.60	4.60	5.30	5.25	4.60	4.60	3.90
Structure$_2$				Spherical			
Sill$_2$				0.70			
Range$_2$				8.60			

Table 18: Log(Total Density) semivariogram parameters, Denham Sound

	1999	2000	2001	2002	2003	2004	2005
Nugget	0.26	0.18	0.62	0.10	0.00	0.32	0.18
Structure	Spherical	Spherical	Spherical	Spherical	Spherical	Spherical	Spherical
Sill	0.81	0.43	0.56	2.69	1.02	0.58	0.61
Range	9.82	4.94	7.49	11.93	5.04	6.37	4.10

Lognormal ordinary kriging estimates were calculated on a 1x1 nautical mile estimation grid using a minimum of 2 and a maximum of 12 data to calculate the estimate at each grid node. For each region circular search neighbourhoods were used with radii of 5 nautical miles for Denham Sound and 6 nautical miles for the Shark Bay North region.

Spatial maps of the resulting density estimates for the Shark Bay North region are displayed in Figure 16 to Figure 22 and for Denham Sound in Figure 23 to Figure 29 along with corresponding location maps of the survey data. These spatial maps show that the lognormal ordinary kriging estimates display similar patterns to the survey data with areas of high and low estimates corresponding with the locations of high and low survey density values respectively. For the Shark Bay North region the high density values are usually concentrated in the west of the Red Cliff fishing ground. For the 1999 survey an area of high scallop densities runs along the western boundary of the region. The area of high estimates for the 2002 survey occupies a smaller area in the southwest of Red Cliff while for 2001 a large area of high density values is located in the northwest of Red Cliff with lower values for the southwest. The spatial maps of the

2002 and 2003 survey data each display two adjacent areas of high estimates in the west and southwest of Red Cliff. For the 2004 and 2005 surveys high estimates are also located in the west of Red Cliff however this area is much smaller in 2005.

For the 1999, 2003, 2004 and 2005 surveys areas with high density values are located towards the northern boundary of the NW Peron fishing ground. The density data for the 2000, 2001 and 2005 surveys also contain some high values further to the south in NW Peron. For the same region, locations with low density values are generally located along the eastern edge of the survey area.

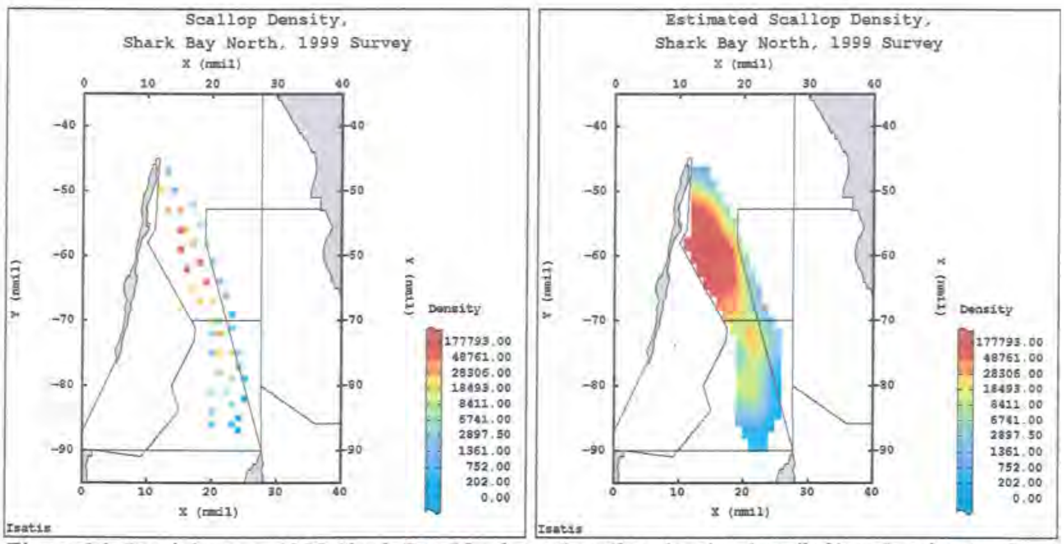

Figure 16: Spatial maps, 1999 Shark Bay North total scallop density data (left) and estimates from lognormal kriging (right)

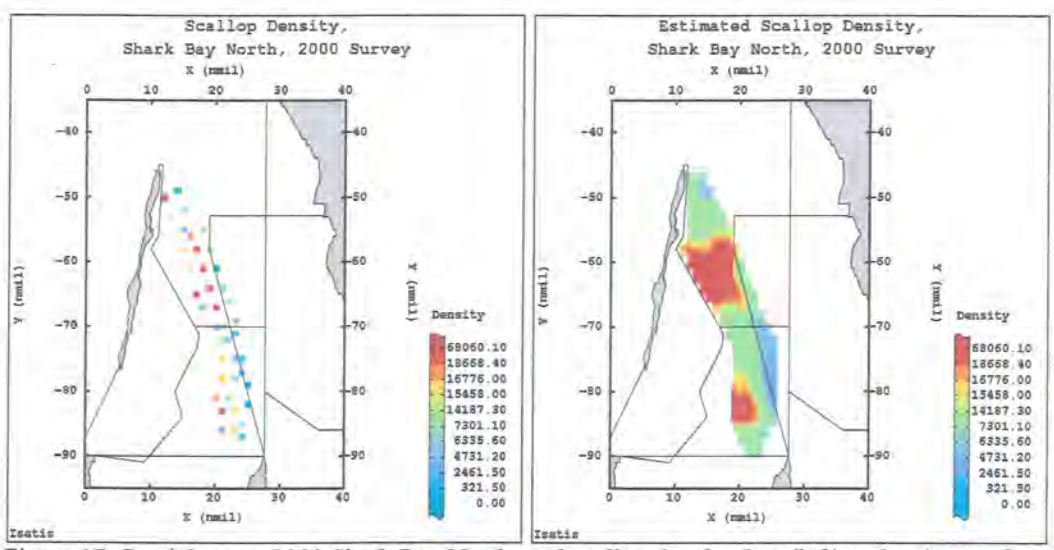

Figure 17: Spatial maps, 2000 Shark Bay North total scallop density data (left) and estimates from lognormal kriging (right)

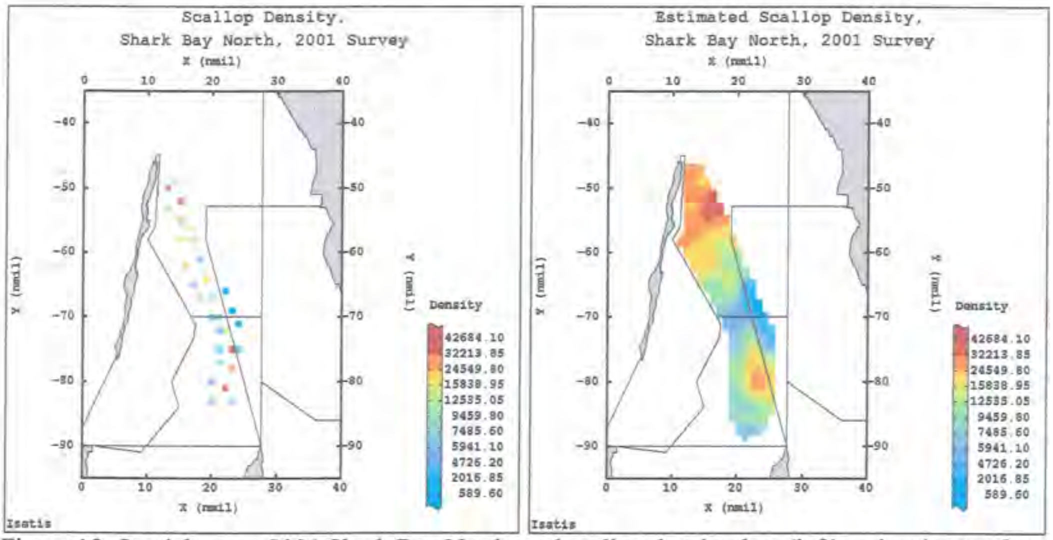

Figure 18: Spatial maps, 2001 Shark Bay North total scallop density data (left) and estimates from lognormal kriging (right)

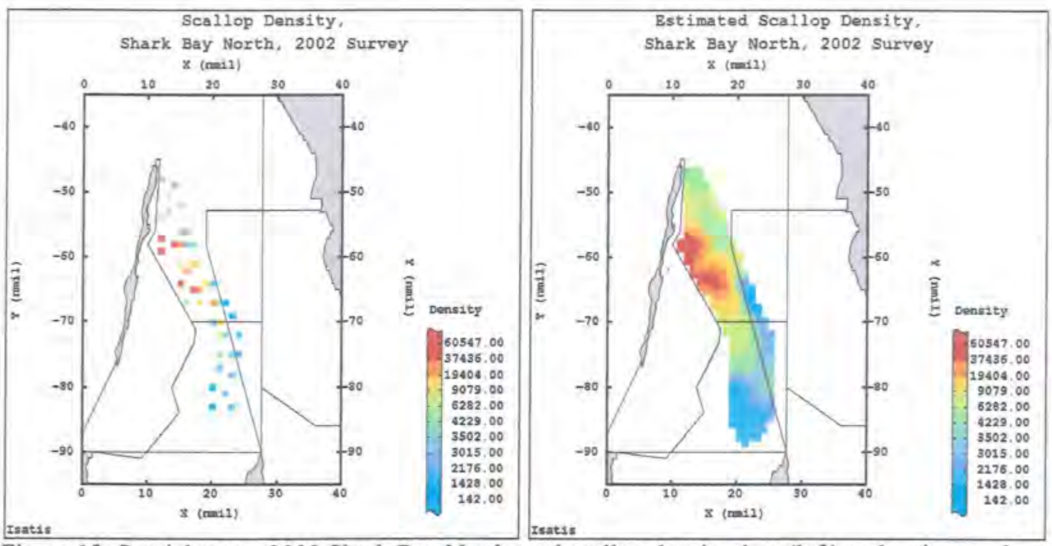

Figure 19: Spatial maps, 2002 Shark Bay North total scallop density data (left) and estimates from lognormal kriging (right)

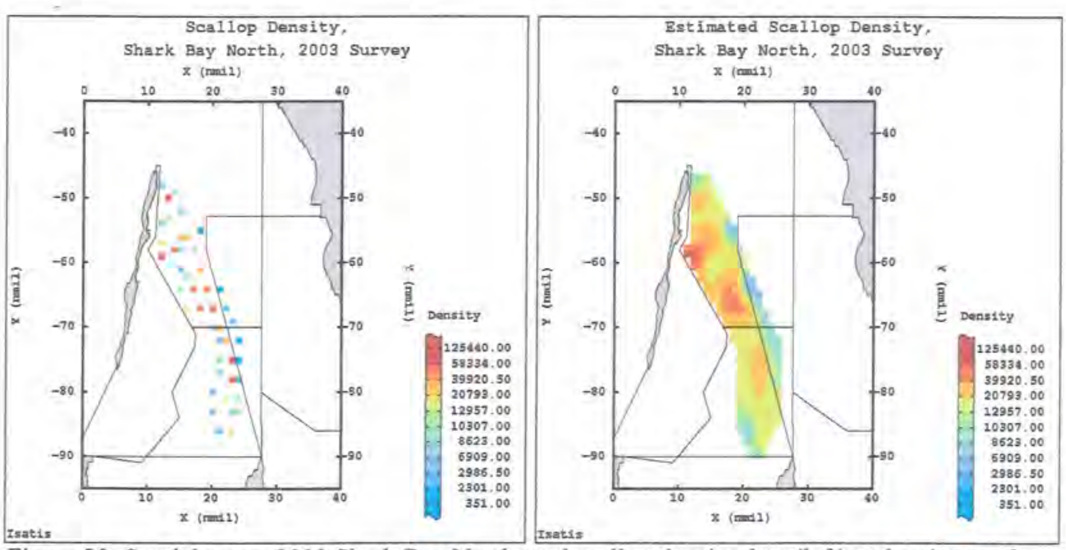

Figure 20: Spatial maps, 2003 Shark Bay North total scallop density data (left) and estimates from lognormal kriging (right)

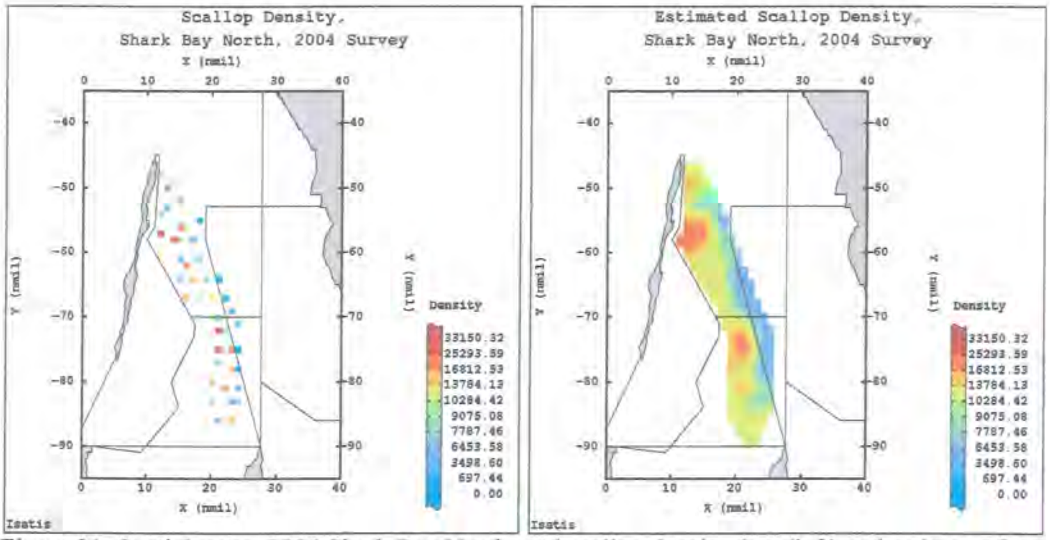

Figure 21: Spatial maps, 2004 Shark Bay North total scallop density data (left) and estimates from lognormal kriging (right)

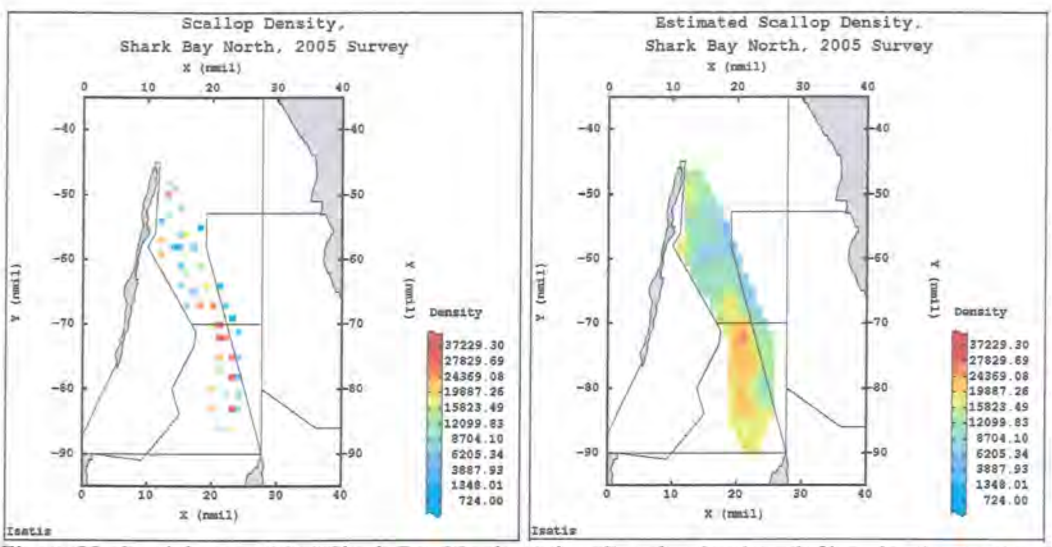

Figure 22: Spatial maps, 2005 Shark Bay North total scallop density data (left) and estimates from lognormal kriging (right)

The spatial distribution of scallops in Denham Sound changes considerably from year to year for the period under consideration. High density values are typically located in the north of the region with low values usually situated towards the south of the region. For the 1999, 2000 and 2005 seasons high density values were concentrated in the northwest of Denham Sound while in 2001 several low values were located in the north with high scallop density estimated in the southeast of the region.

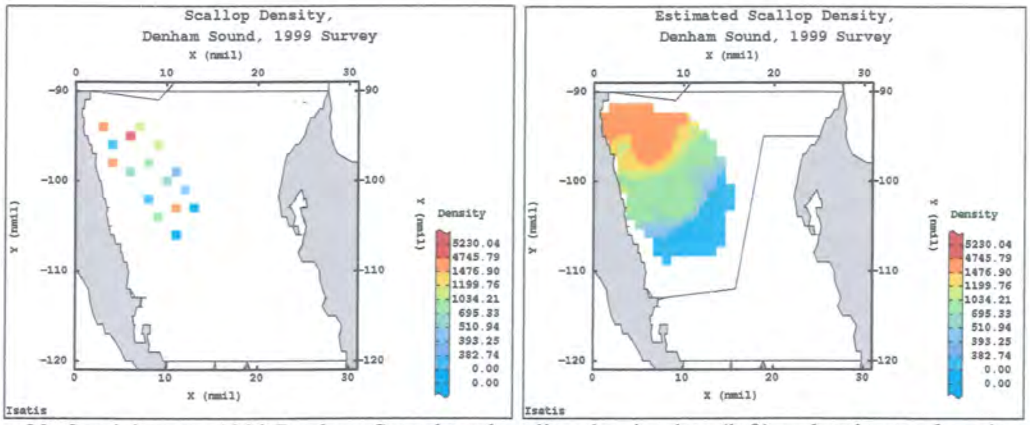

Figure 23: Spatial maps, 1999 Denham Sound total scallop density data (left) and estimates from lognormal kriging (right)

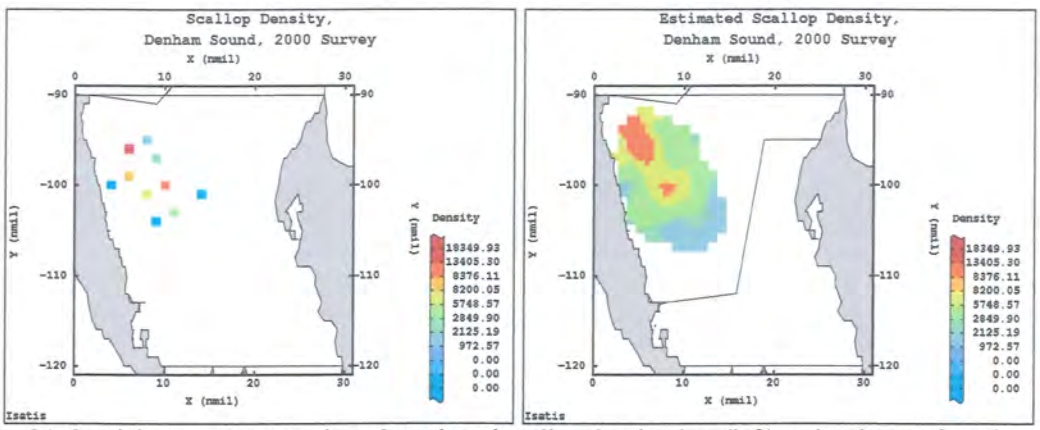

Figure 24: Spatial maps, 2000 Denham Sound total scallop density data (left) and estimates from lognormal kriging (right)

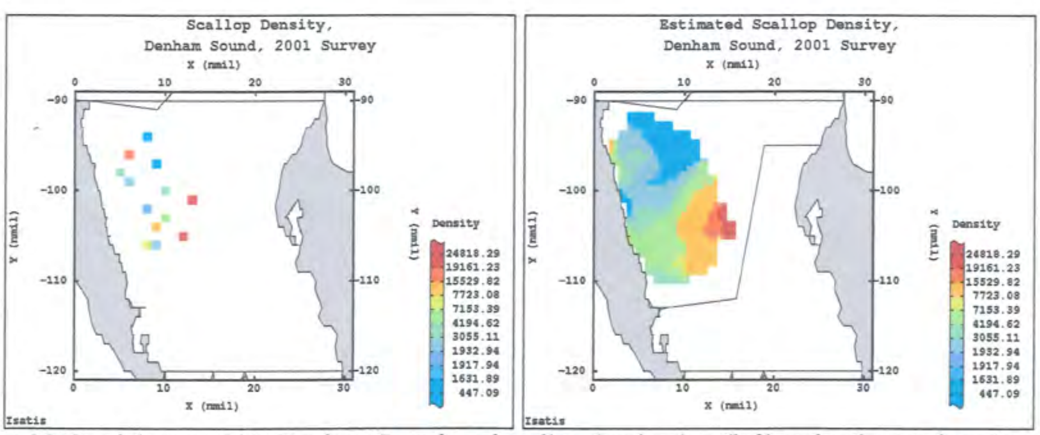

Figure 25: Spatial maps, 2001 Denham Sound total scallop density data (left) and estimates from lognormal kriging (right)

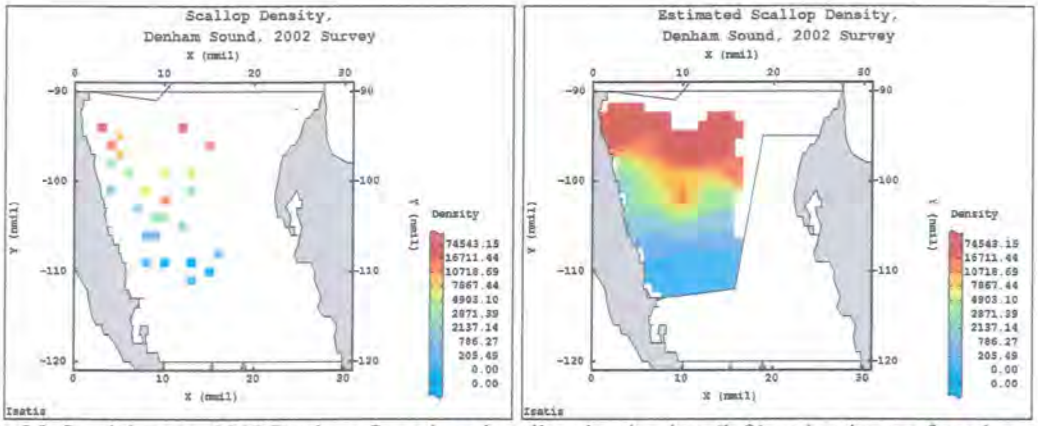

Figure 26: Spatial maps, 2002 Denham Sound total scallop density data (left) and estimates from lognormal kriging (right)

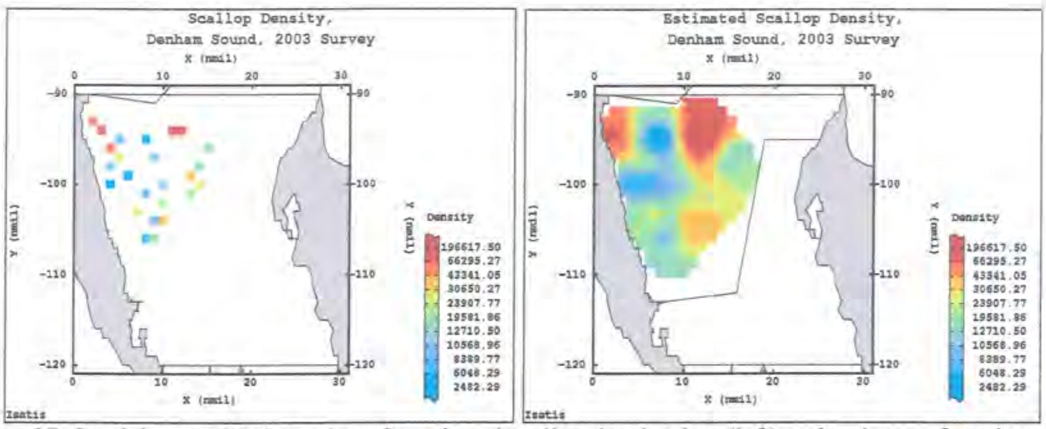

Figure 27: Spatial maps, 2003 Denham Sound total scallop density data (left) and estimates from lognormal kriging (right)

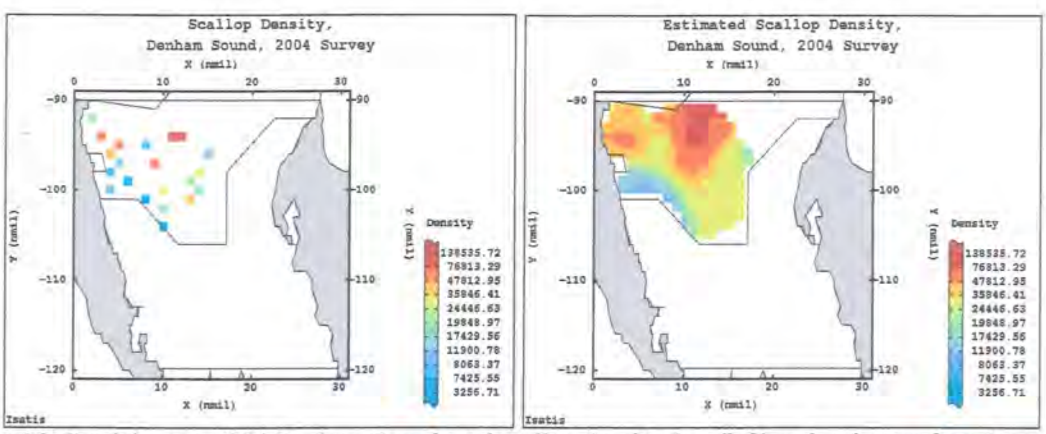

Figure 28: Spatial maps, 2004 Denham Sound total scallop density data (left) and estimates from lognormal kriging (right)

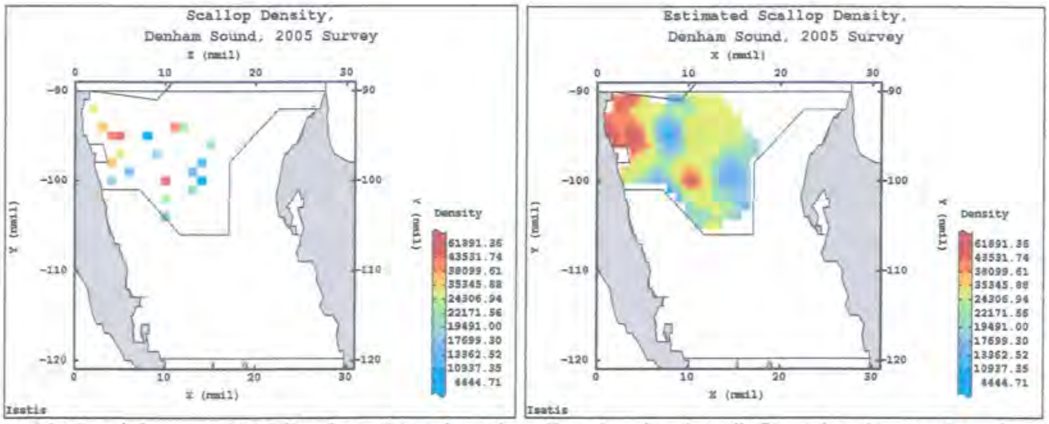

Figure 29: Spatial maps, 2005 Denham Sound total scallop density data (left) and estimates from lognormal kriging (right)

Estimates for the density of recruit scallops were also calculated from the survey data. Lognormal ordinary kriging was used for this purpose as the recruit density data have a considerably strong positive skew. The relevant input parameters from Mueller et al. (2004) and Bloom et al. (2006) were also used in the estimation. The additive constants used when calculating the logarithms of the data are listed in Table 19 and the semivariogram model parameters are listed in Table 20 and Table 21.

Table 19: Constants added to recruit scallop density survey data

Region	1999	2000	2001	2002	2003	2004	2005
SB North	50	1500	1	150	50	70	0
Denham	50	1500	1	150	50	2.5	100

Table 20: Log(Recruit Density) semivariogram parameters, Shark Bay North region

	1999	2000	2001	2002	2003	2004	2005
Nugget	2.00	0.40	0.20	0.38	0.99	1.38	0.97
$Structure_1$	Spherical	Spherical	Spherical	Spherical	Spherical	Spherical	Spherical
$Sill_1$	3.12	0.42	0.70	0.53	1.59	1.17	0.98
$Range_1$	11.40	4.60	4.00	2.40	5.25	4.70	9.70
$Structure_2$			Spherical	Spherical			
$Sill_2$			0.28	1.52			
$Range_2$			8.40	10.90			

Table 21: Log(Recruit Density) semivariogram parameters, Denham Sound

	1999	2000	2001	2002	2003	2004	2005
Nugget	0.47	0.24	0.36	0.83	0.00	0.90	0.96
Structure	Spherical	Spherical	Spherical	Spherical	Spherical	Spherical	Spherical
Sill	1.21	0.50	1.16	2.67	3.00	3.60	1.82
Range	10.00	4.36	7.87	11.71	5.70	4.40	3.50

The lognormal ordinary kriging estimates were calculated on a 1x1 nautical mile grid using a minimum of 2 and a maximum of 12 data to calculate the estimate at each grid node. For both regions circular search neighbourhoods were used with radii of 5 nautical miles for Denham Sound and 6 nautical miles for the Shark Bay North region.

Spatial maps of the estimated recruit density for the Shark Bay North region together with the relevant recruit density survey data are displayed in Figure 37 to Figure 36. These show that for each case the estimated recruit density is representative of the recruit densities measured by the corresponding survey. These maps also show that for the 1999 survey the highest estimated recruit densities are located in the west of the Red Cliff region with areas of low estimated recruit density occupying the southeast of NW Peron and the eastern and northern parts of Red Cliff. For 2000, areas of high estimated recruit density are located in the southwest of Red Cliff and in the south of NW Peron while for 2001 high recruit density estimates are given for the northwest and west of Red Cliff as well as for the centre-east of NW Peron with a large area of low estimated recruit density occupying the south of Red Cliff and north of NW Peron. The recruit density estimates for 2002 display high values along the west and southwest of Red Cliff with areas of low estimated recruit density located in the south and northeast of NW Peron and in the southeast and northwest of Red Cliff. For 2003 areas of high recruit density estimates were located in the northwest, west and southwest of Red Cliff as well as in the northwest of NW Peron with low density estimates given for the south and east of NW Peron and in the east of Red Cliff. For both the 2004 and 2005 surveys an area of high recruit density estimates occupies the west of NW Peron with low recruit density estimates for the centre of Red Cliff however for 2004 small areas of high recruit density estimates are also located along the west/north-western boundary of Red Cliff.

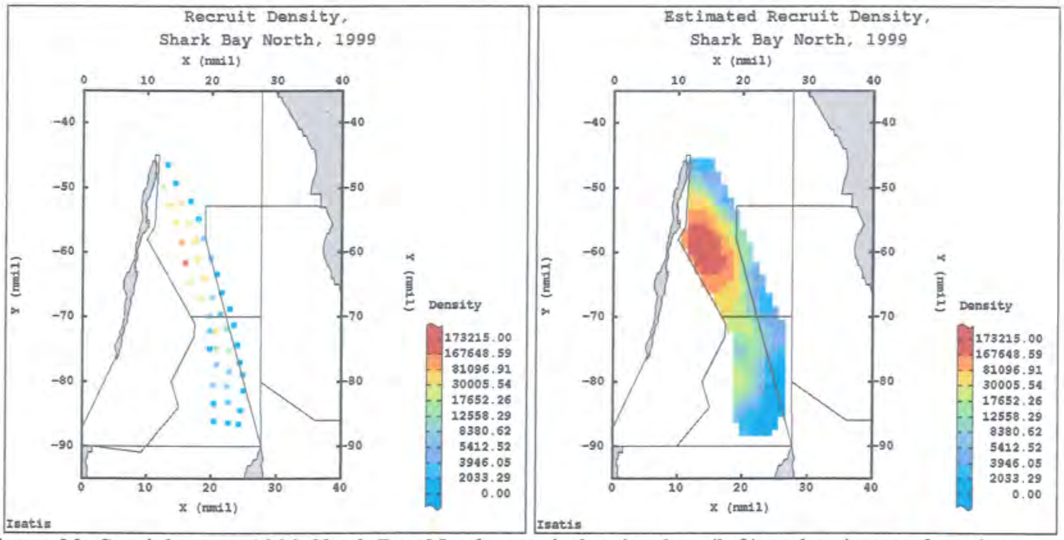

Figure 30: Spatial maps, 1999 Shark Bay North recruit density data (left) and estimates from lognormal kriging (right)

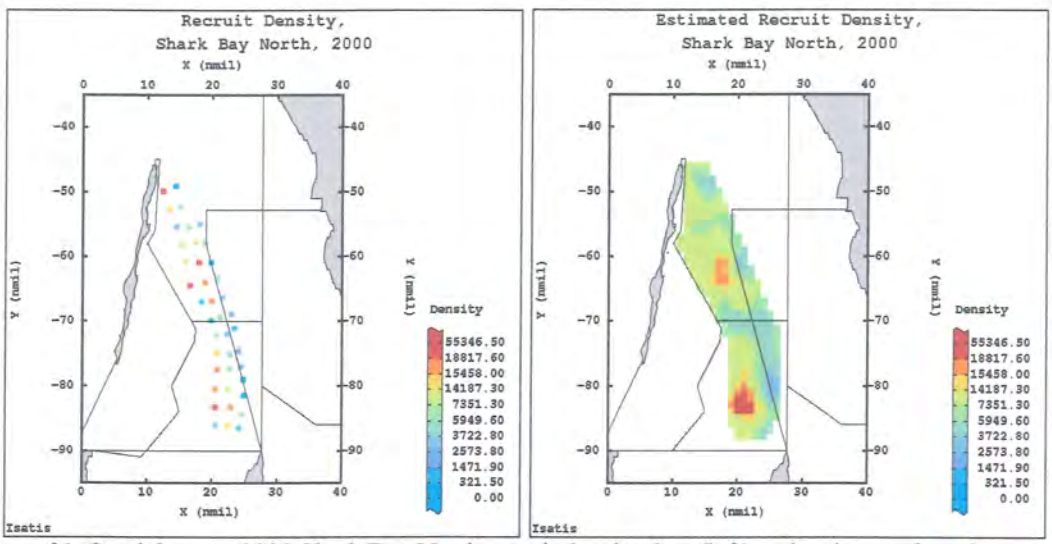

Figure 31: Spatial maps, 2000 Shark Bay North recruit density data (left) and estimates from lognormal kriging (right)

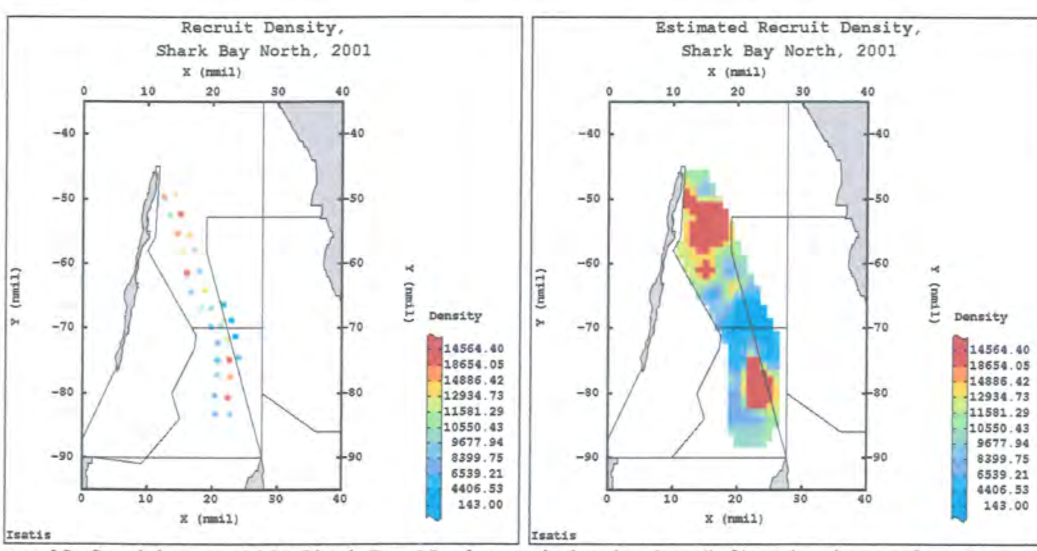

Figure 32: Spatial maps, 2001 Shark Bay North recruit density data (left) and estimates from lognormal kriging (right)

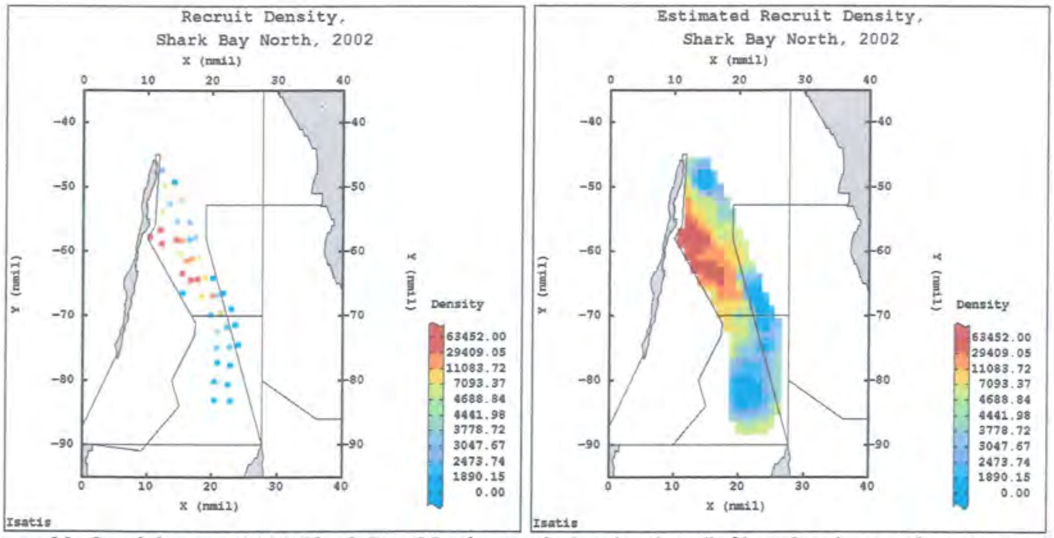

Figure 33: Spatial maps, 2002 Shark Bay North recruit density data (left) and estimates from lognormal kriging (right)

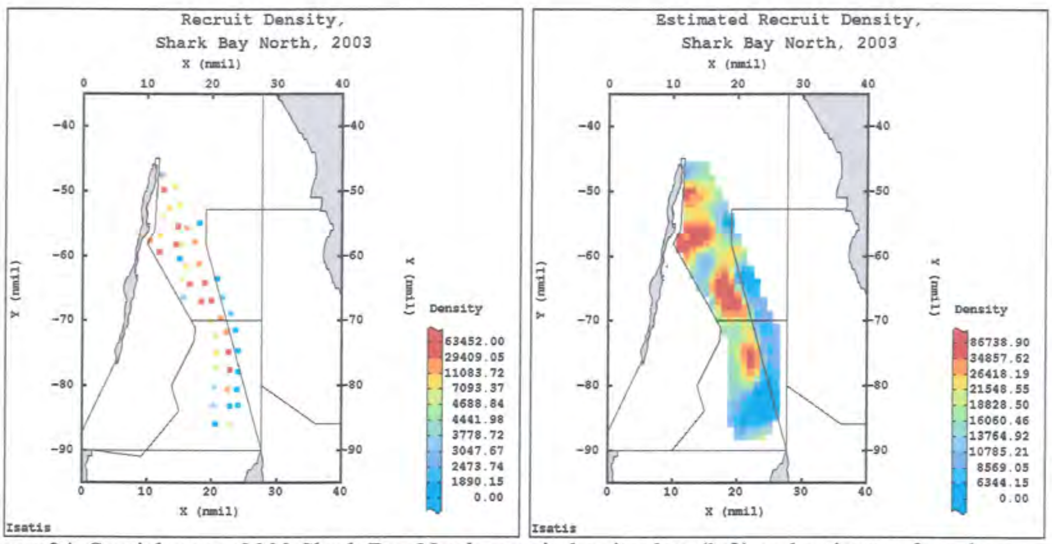

Figure 34: Spatial maps, 2003 Shark Bay North recruit density data (left) and estimates from lognormal kriging (right)

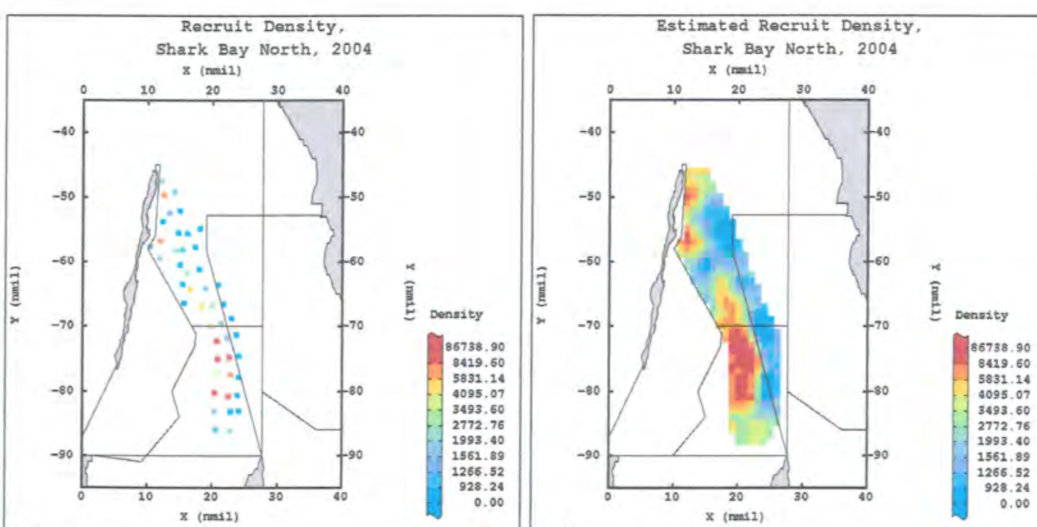

Figure 35: Spatial maps, 2004 Shark Bay North recruit density data (left) and estimates from lognormal kriging (right)

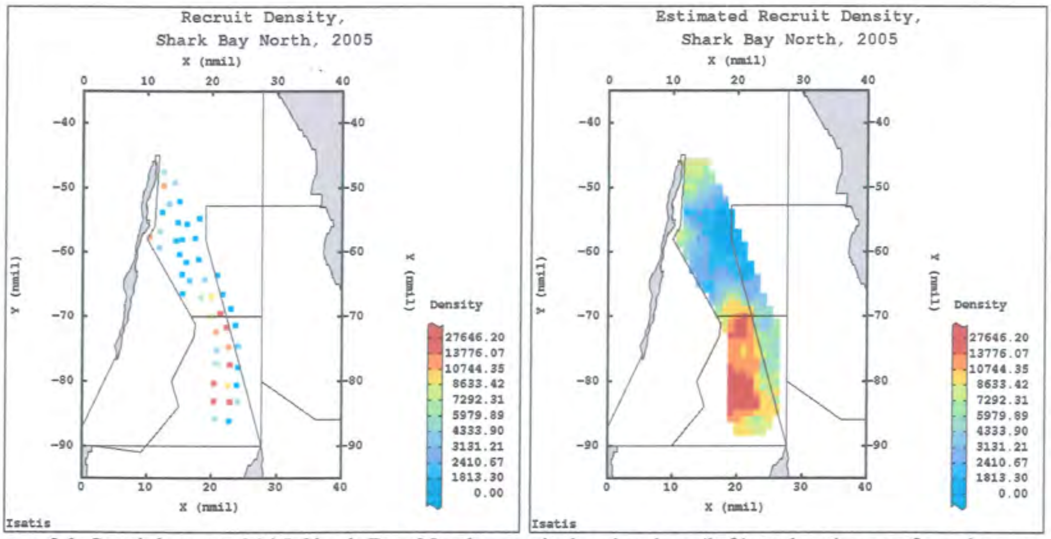

Figure 36: Spatial maps, 2005 Shark Bay North recruit density data (left) and estimates from lognormal kriging (right)

4.1.2. Total Scallop Density Estimates, Total Scallop Catch of Both Fleets Combined and Combined Catch Rate

The spatial maps of the scallop survey density estimates for each year, discussed in the previous section, are compared below with the total scallop catch and catch rate data for the subsequent season. For each map the levels have been coded using the deciles of the relevant distribution with high values indicated by red and low values by blue (see Appendix A for detail). These comparisons indicate whether the pre-season survey data have similar spatial patterns to the catch data for the following season. The spatial maps of the scallop density estimates, the total catch and catch rate for each 1 nautical mile block of the Shark Bay North region are presented in Figure 37 to Figure 42. These maps show that areas with high scallop density estimates generally correspond to locations with large total catches and high catch rates.

For each case the areas of high density estimates given for the west of the Red Cliff fishing ground contain many locations for which a high total scallop catch and catch rate was recorded in the following season. A small region of high density estimates located in the east of Red Cliff in the 2000 survey also corresponds with an area of high catch and catch rate values for the 2001 season. Similarly, areas of high density estimates located in NW Peron for the 2001, 2003 and 2004 surveys match well with many locations of large total catch values for the next season however few locations of high catch rates were recorded within these areas in the following season. In addition to this, areas of low density estimates, particularly along the east of Red Cliff and NW Peron, correspond well to locations with small total catch values and low catch rates in the next season. In the 2002, 2004 and 2005 seasons however several locations with very high catch rate values are found within the areas for which low scallop densities were estimated in the pre-season survey. The spatial patterns found in the catch rate data appear to reflect the relevant pre-season survey density estimates better than the total catch spatial patterns, especially in NW Peron.

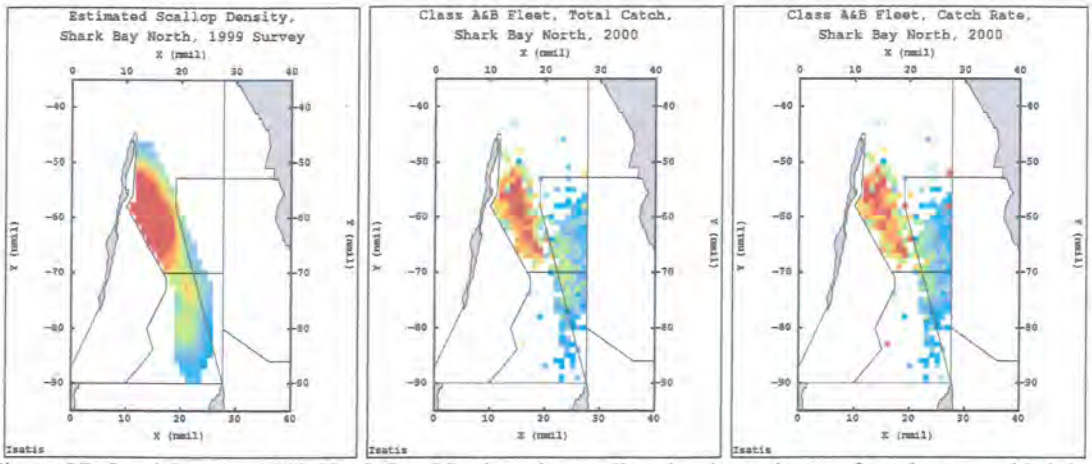

Figure 37: Spatial maps, 1999 Shark Bay North region scallop density estimates from lognormal kriging (left), 2000 total scallop catch (centre) and 2000 scallop catch rate (right)

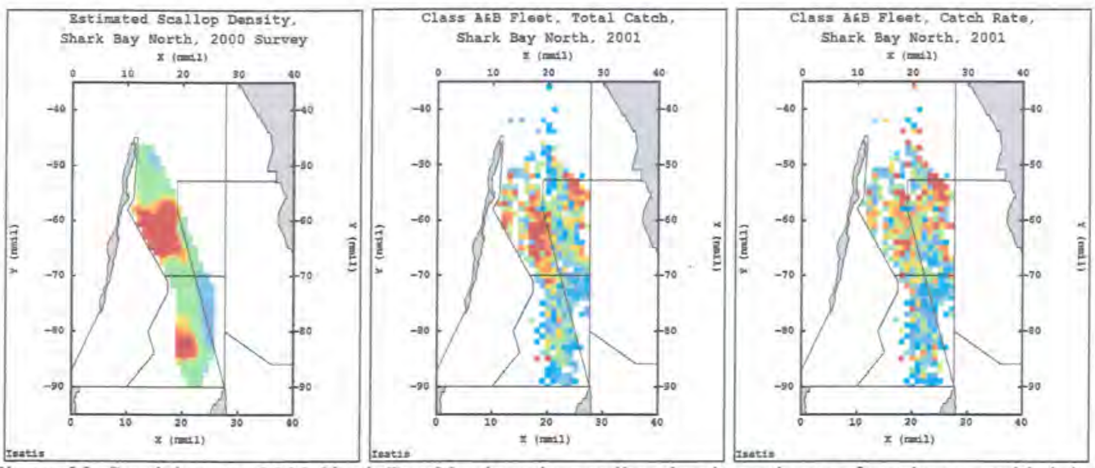

Figure 38: Spatial maps, 2000 Shark Bay North region scallop density estimates from lognormal kriging (left), 2001 total scallop catch (centre) and 2001 scallop catch rate (right)

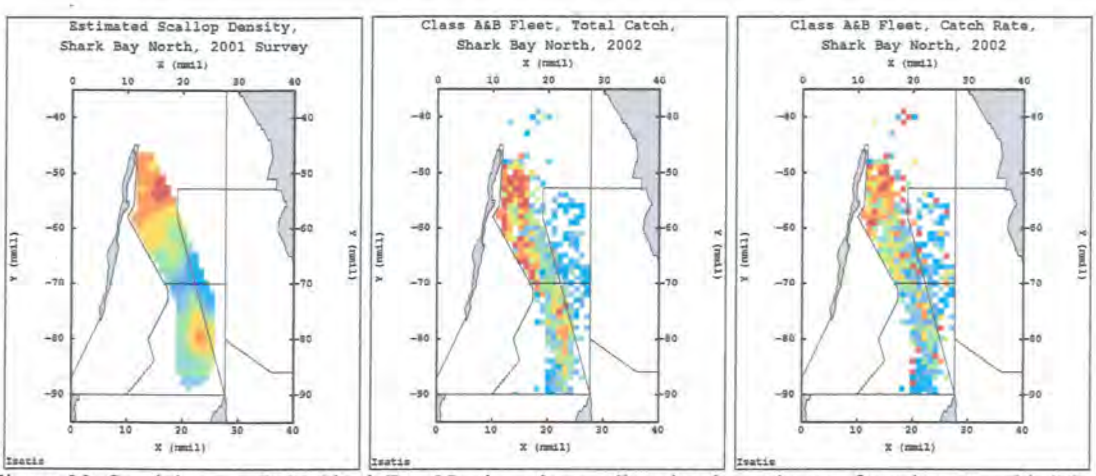

Figure 39: Spatial maps, 2001 Shark Bay North region scallop density estimates from lognormal kriging (left), 2002 total scallop catch (centre) and 2002 scallop catch rate (right)

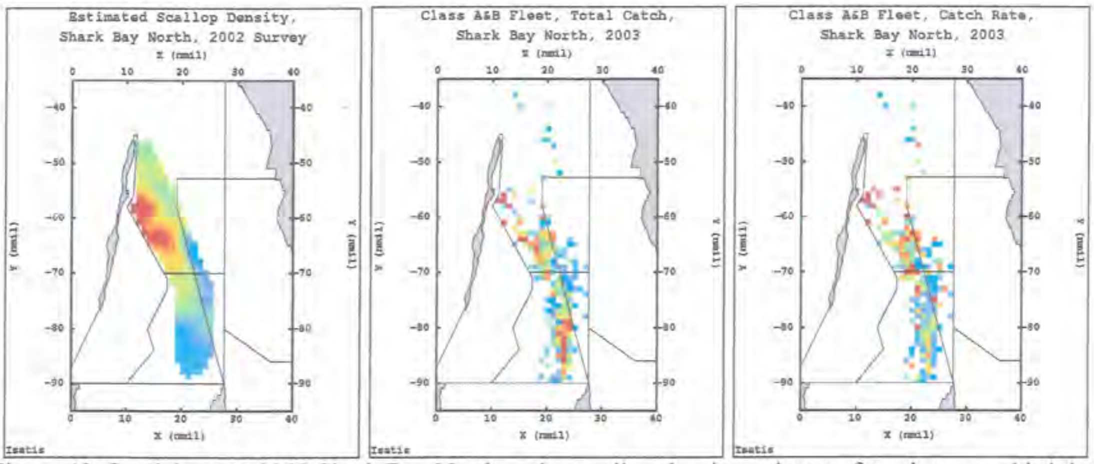

Figure 40: Spatial maps, 2002 Shark Bay North region scallop density estimates from lognormal kriging (left), 2003 total scallop catch (centre) and 2003 scallop catch rate (right)

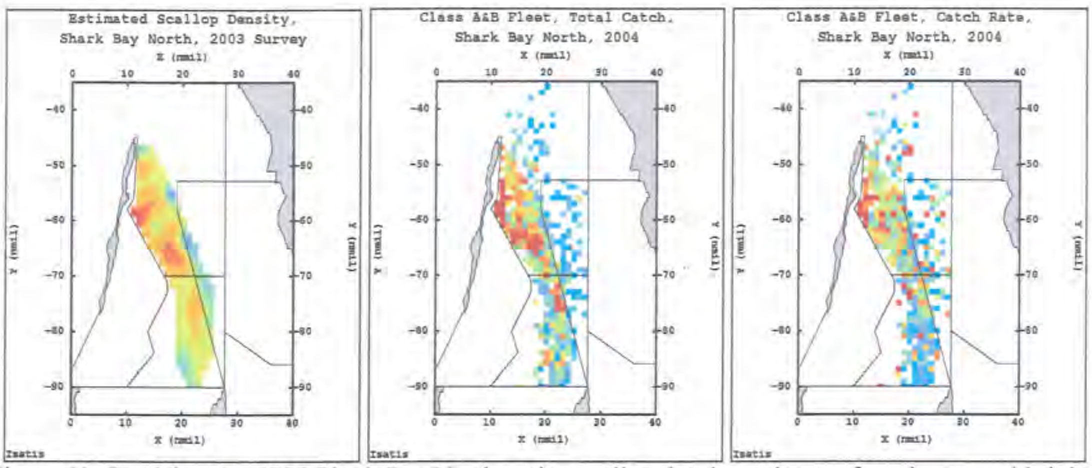

Figure 41: Spatial maps, 2003 Shark Bay North region scallop density estimates from lognormal kriging (left), 2004 total scallop catch (centre) and 2004 scallop catch rate(right)

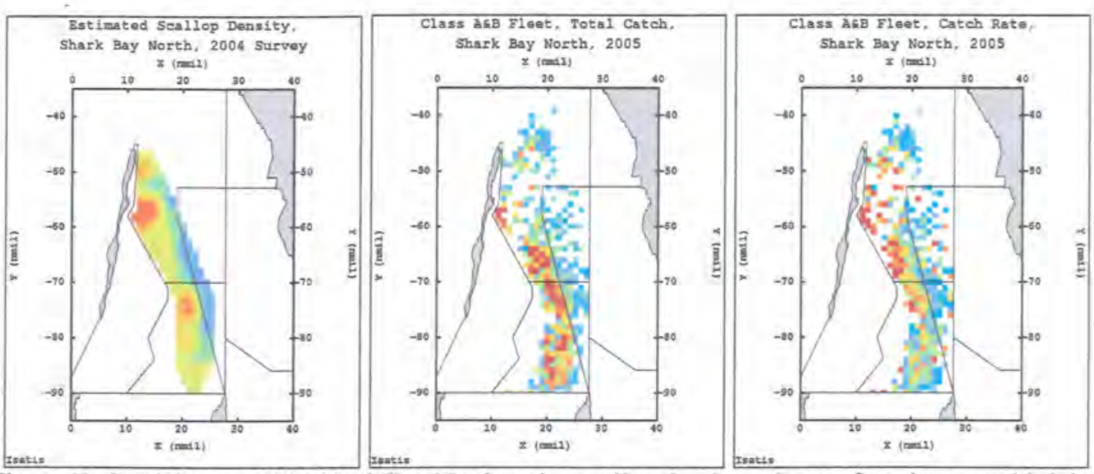

Figure 42: Spatial maps, 2004 Shark Bay North region scallop density estimates from lognormal kriging (left), 2005 total scallop catch (centre) and 2005 scallop catch rate (right)

Spatial maps of the estimated scallop density and the subsequent total scallop catch and catch rates for Denham Sound are displayed in Figure 43 to Figure 48. As for Shark Bay North these spatial maps have been coded using the decile values of the relevant distribution. These show that the areas of high and low density estimates in the maps for the 1999, 2000 and 2001 surveys typically do not correspond with locations of high and low total catch and catch rates in the following season. In the density estimate spatial maps for the 2002, 2003 and 2004 surveys however the areas of high values given for the north of the region match well with locations of large total catch and high catch rate values for the subsequent season. Similarly, the areas of low estimated scallop density for the 2002 to 2004 surveys contain several locations of low scallop catch values and some locations with low catch rates in the following season. These spatial maps suggest that for Denham sound the scallop survey density estimates for the 2002 to 2004 scallop surveys provide a good indication of the spatial patterns observed in the total scallop catch and catch rate data for the subsequent fishing season.

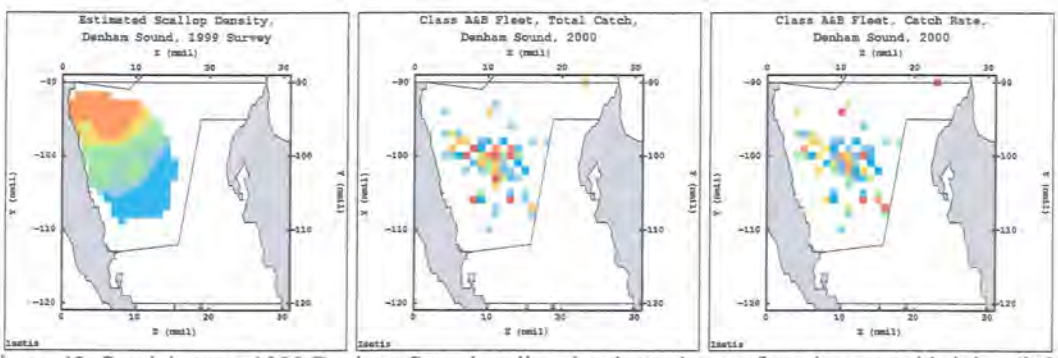

Figure 43: Spatial maps, 1999 Denham Sound scallop density estimates from lognormal kriging (left), 2000 total scallop catch (centre) and 2000 scallop catch rate (right)

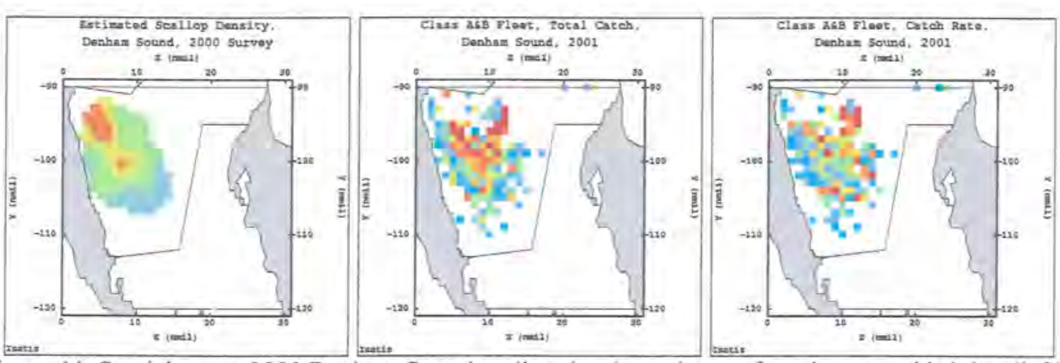

Figure 44: Spatial maps, 2000 Denham Sound scallop density estimates from lognormal kriging (left) , 2001 total scallop catch (centre) and 2001 scallop catch rate (right)

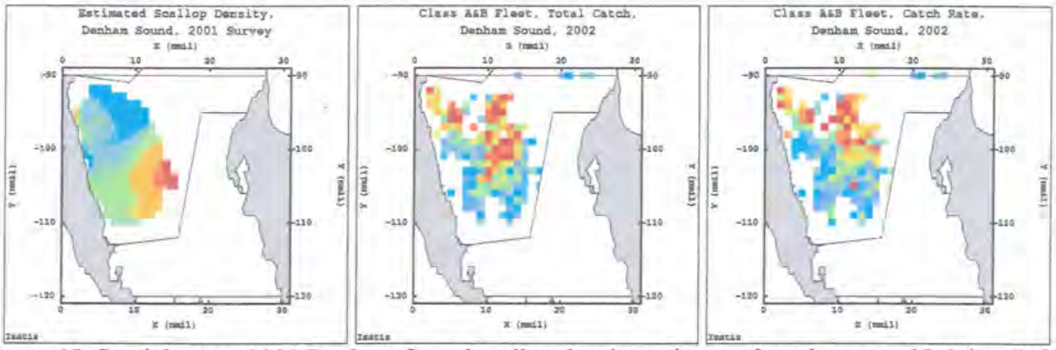

Figure 45: Spatial maps, 2001 Denham Sound scallop density estimates from lognormal kriging (left), 2002 total scallop catch (centre) and 2002 scallop catch rate (right)

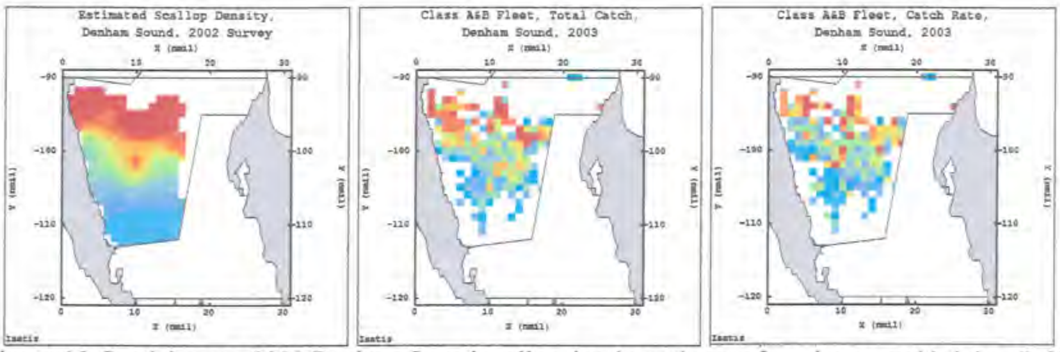

Figure 46: Spatial maps, 2002 Denham Sound scallop density estimates from lognormal kriging (left), 2003 total scallop catch (centre) and 2003 scallop catch rate (right)

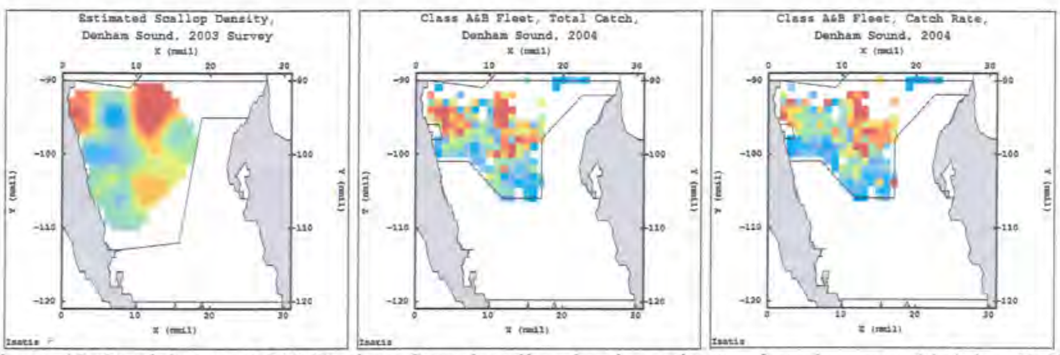

Figure 47: Spatial maps, 2003 Denham Sound scallop density estimates from lognormal kriging (left), 2004 total scallop catch (centre) and 2004 scallop catch rate (right)

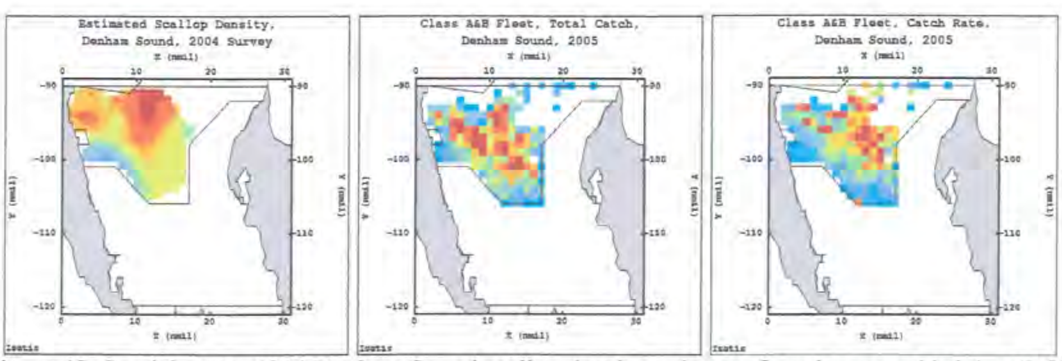

Figure 48: Spatial maps, 2004 Denham Sound scallop density estimates from lognormal kriging (left), 2005 total scallop catch (centre) and 2005 scallop catch rate (right)

4.1.3. Total Pre-Season Fishing Effort of the Class B Fleet and Total Scallop Catch of the Class A Fleet

Spatial maps of the scallop survey density estimates are now compared with the pre-season fishing effort of the Class B fleet and the total scallop catch of the Class A fleet for the subsequent year. These maps display the areas that the two fleets fished and allow the spatial patterns of the Class B pre-season effort and the Class A catch to be contrasted to asses if there is a negative impact of pre-season fishing on the scallop catch. Of particular interest are the catch values achieved by the Class A fleet at locations also fished by the Class B fleet prior to the start of the scallop season. The relevant spatial maps for the Shark Bay North region are displayed in Figure 49 through to Figure 54. The first observation noted from these maps is that the pre-season fishing effort of the Class B fleet is generally concentrated in areas where the Class A fleet do not fish. The Class A fleet catch values are largely located in the west of the Red Cliff fishing ground while the Class B pre-season effort is focused in the north, centre and east of Red Cliff as well within NW Peron and the Class A vessel trawl closure. Similarly, the areas of high scallop density estimates are fished very little by the Class B fleet before the start of the scallop season.

In each season there are two main areas of high Class B pre-season effort with the first located in the north of Red Cliff and the second located in the south of Red Cliff and north of NW Peron. Although the locations of the first area of high pre-season effort coincide very little with the locations of Class A scallop catch the second area overlaps with the Class A catch locations considerably in some seasons. For the 2000, 2003 and 2005 seasons there are very few locations with both Class B pre-season effort and Class A scallop catch. For the 2001 and 2004 fishing seasons several locations in the centre and south of Red Cliff and in NW Peron contain both pre-season effort and Class A fleet catch values. The spatial maps for the 2002 season have the greatest number of common locations with many locations in the east and south of Red Cliff and across NW Peron containing both pre-season effort and Class A fleet catch values.

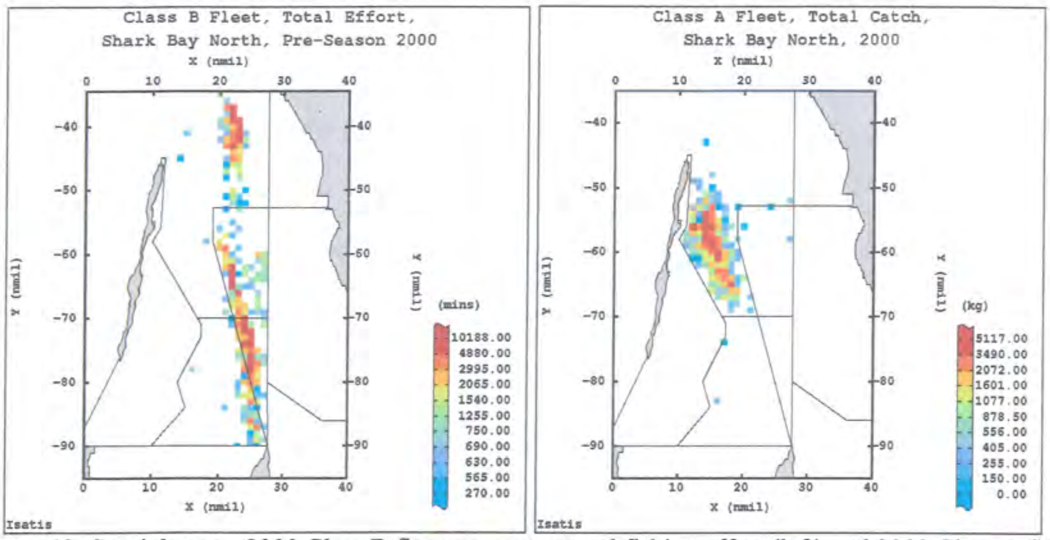

Figure 49: Spatial maps, 2000 Class B fleet pre-season total fishing effort (left) and 2000 Class A fleet total scallop catch (right)

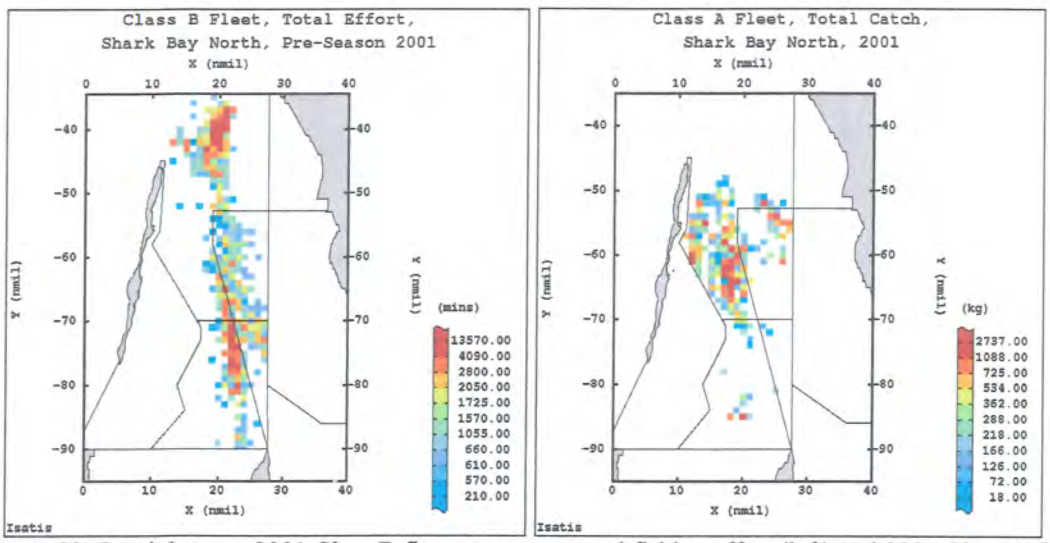

Figure 50: Spatial maps, 2001 Class B fleet pre-season total fishing effort (left) and 2001 Class A fleet total scallop catch (right)

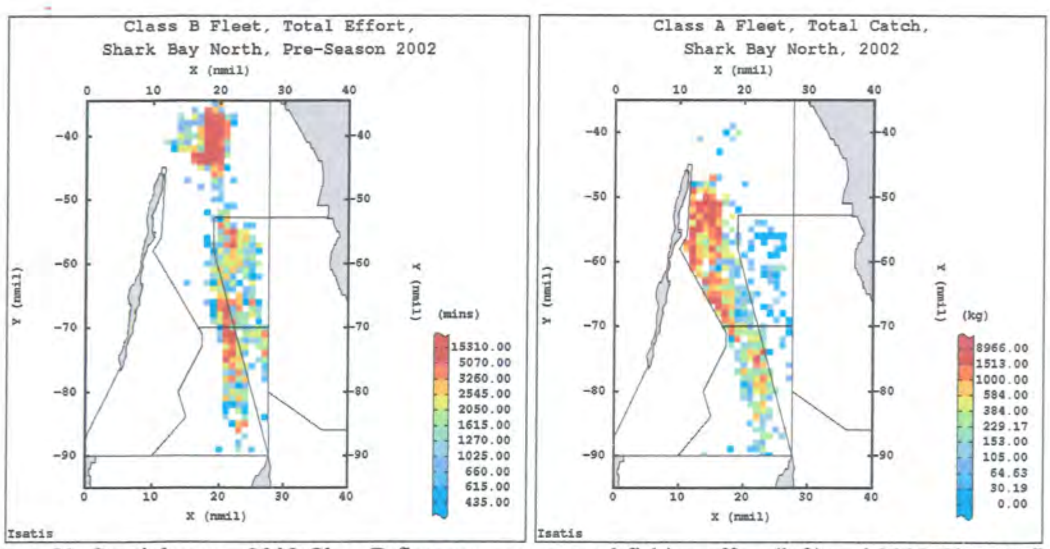

Figure 51: Spatial maps, 2002 Class B fleet pre-season total fishing effort (left) and 2002 Class A fleet total scallop catch (right)

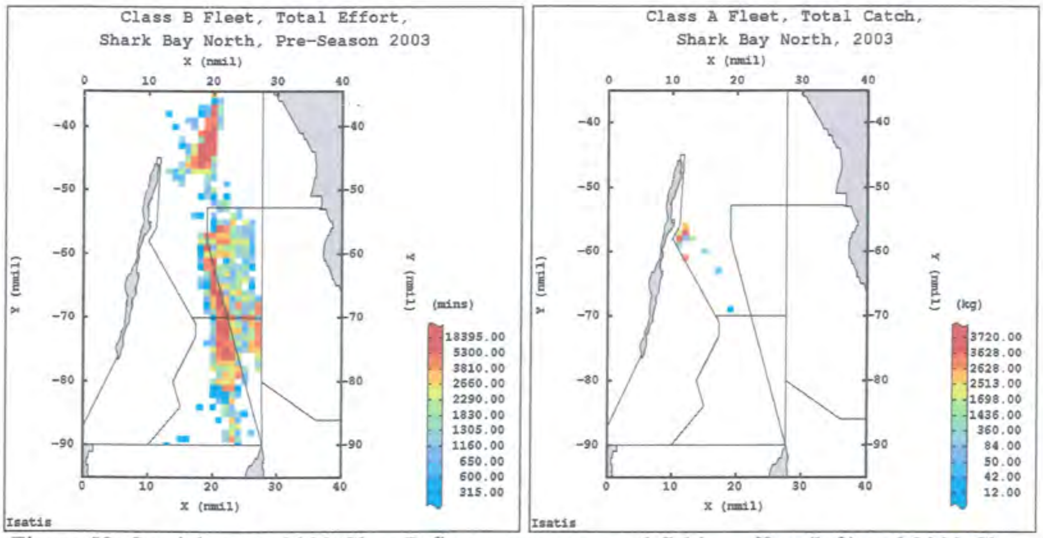

Figure 52: Spatial maps, 2003 Class B fleet pre-season total fishing effort (left) and 2003 Class A fleet total scallop catch (right)

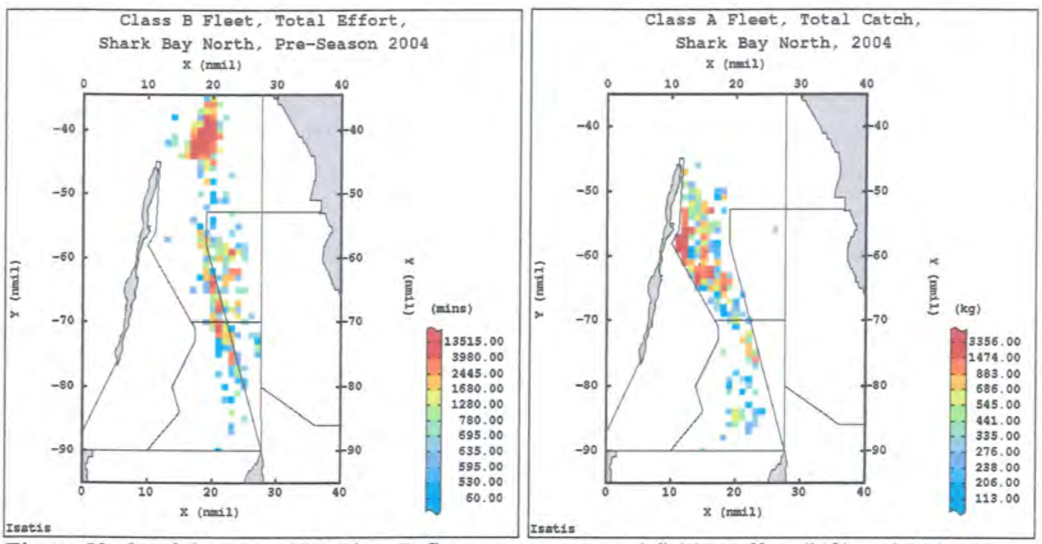

Figure 53: Spatial maps, 2004 Class B fleet pre-season total fishing effort (left) and 2004 Class A fleet total scallop catch (right)

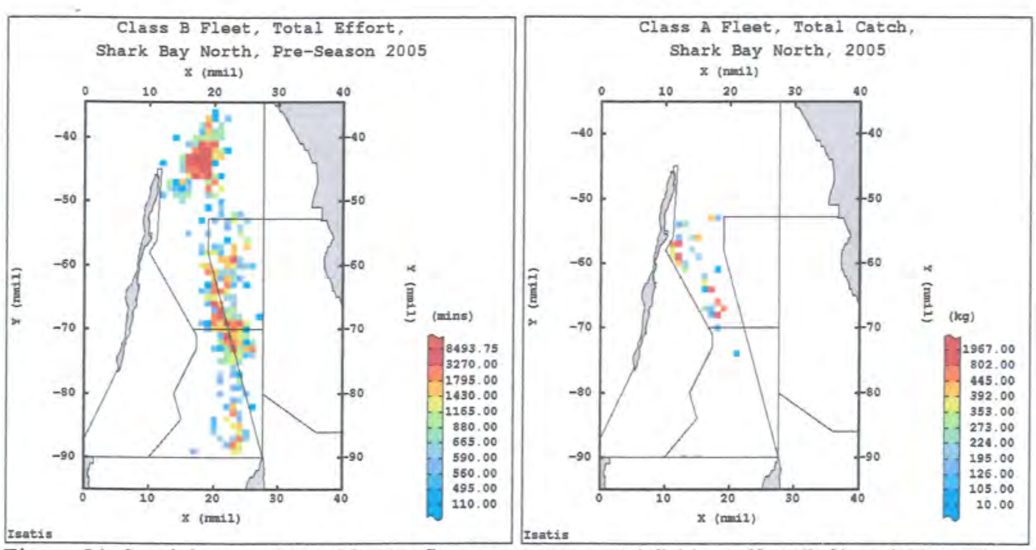

Figure 54: Spatial maps, 2005 Class B fleet pre-season total fishing effort (left) and 2005 Class A fleet total scallop catch (right)

The relevant spatial maps for the Denham Sound region are displayed in Figure 55 to Figure 57. Maps of the 2000 season have not been displayed as for this season no catch for the Class A fleet was located in Denham Sound. In addition to this, maps for the 2004 and 2005 seasons are not shown as in these years the Class B fleet did not fish in Denham Sound prior to the start of the scallop fishing in Denham Sound. For the 2001 and 2002 seasons very few of the locations that recorded high pre-season fishing effort values were situated within areas of high estimated scallop density from the previous survey.. The maps for the 2001 and 2002 season each contain a few common locations in the northwest of Denham Sound while the maps for the 2003 season have the largest number of common locations also located in the northwest of the region. There are no marked patterns in these spatial maps between locations of high pre-season Class B fleet effort and the subsequent Class A fleet scallop catch.

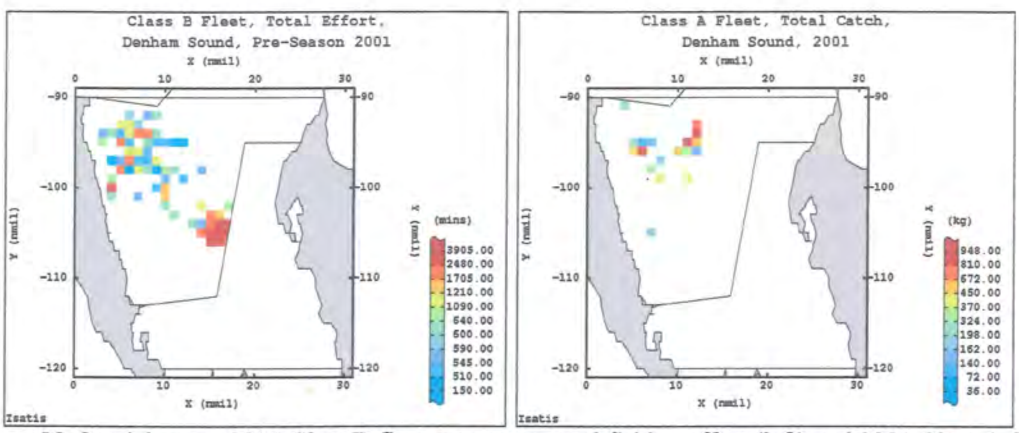

Figure 55: Spatial maps, 2001 Class B fleet pre-season total fishing effort (left) and 2001 Class A fleet total scallop catch (right)

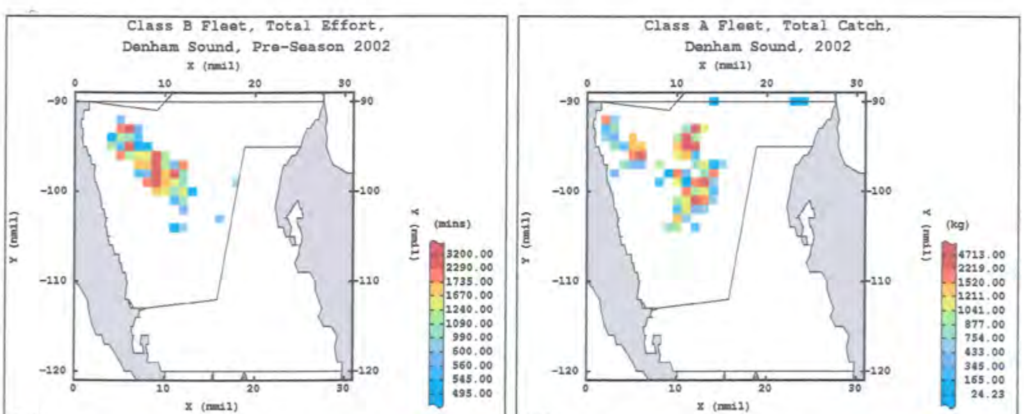

Figure 56: Spatial maps, 2002 Class B fleet pre-season total fishing effort (left) and 2002 Class A fleet total scallop catch (right)

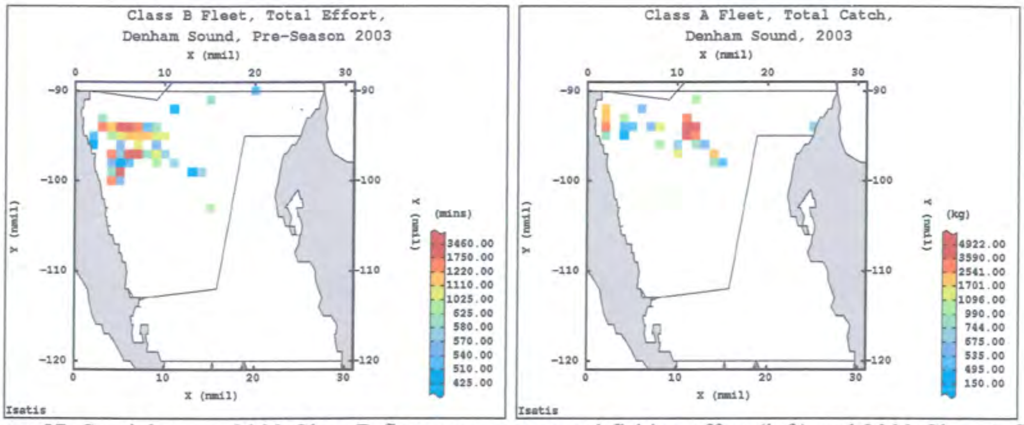

Figure 57: Spatial maps, 2003 Class B fleet pre-season total fishing effort (left) and 2003 Class A fleet total scallop catch (right)

4.1.4. Total Fishing Effort of the Class B Fleet and Total Scallop Catch of both Fleets Combined

To further investigate the interaction between the two fishing fleets spatial maps of the total fishing effort for the Class B fleet are contrasted with spatial maps of the total scallop catch recorded for both fleets combined. The maps of these data for the Shark Bay North region are displayed in Figure 58 to Figure 63. These show that for Shark Bay North the fishing effort of the Class B fleet is generally concentrated in the far north, middle and south of Red Cliff and across NW Peron as well as within the Class A vessel trawl closure. Very few high total effort values for the Shark Bay North region are located within areas of high estimated scallop density for the relevant pre-season survey.

The area in the west of Red Cliff for which high total scallop catch values are typically recorded contains very few, if any, locations for which a Class B fleet effort value has been recorded in each season. For the 2000 and 2001 fishing seasons the areas in the southeast of Red Cliff and across the east of NW Peron for which many high Class B fleet effort values are located typically correspond with locations for which relatively low scallop catches were recorded. For the 2002 to 2005 seasons the areas with many high Class B fleet effort values in the east and southeast of Red Cliff correspond with locations of low scallop catch. For each of these seasons however locations of high total scallop catch found within NW Peron correspond very well with locations of high Class B fleet effort. The locations in the east of Red Cliff for which several high total catch values were recorded for the 2001 season recorded mostly low Class B fleet effort values. These maps show that for Red Cliff the areas of high Class B fleet effort typically contain many locations at which low total scallop catch values were recorded while in NW Peron areas with high total scallop catch coincide with locations of high Class B fleet effort.

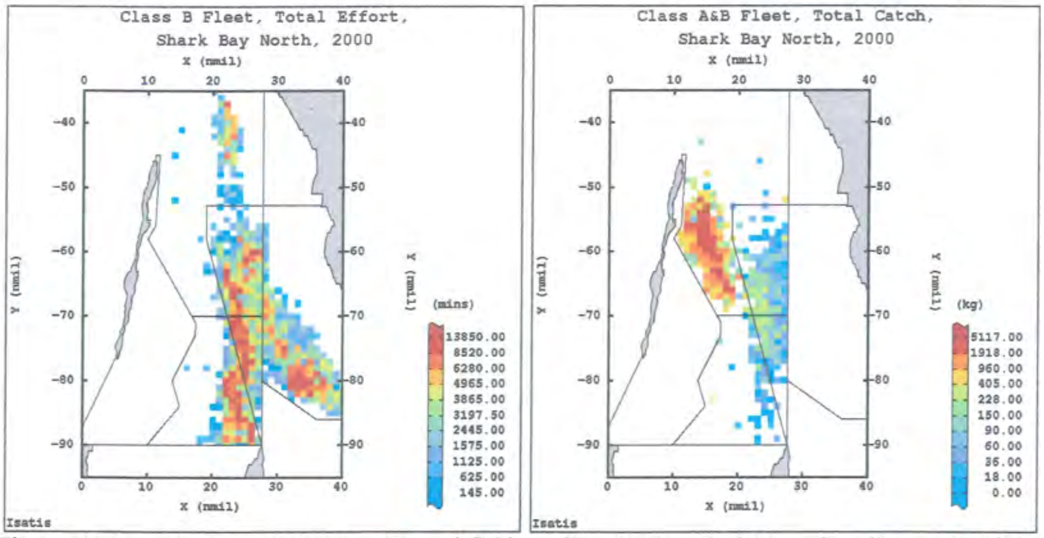

Figure 58: Spatial maps, 2000 Class B total fishing effort (left) and 2000 total scallop catch (right)

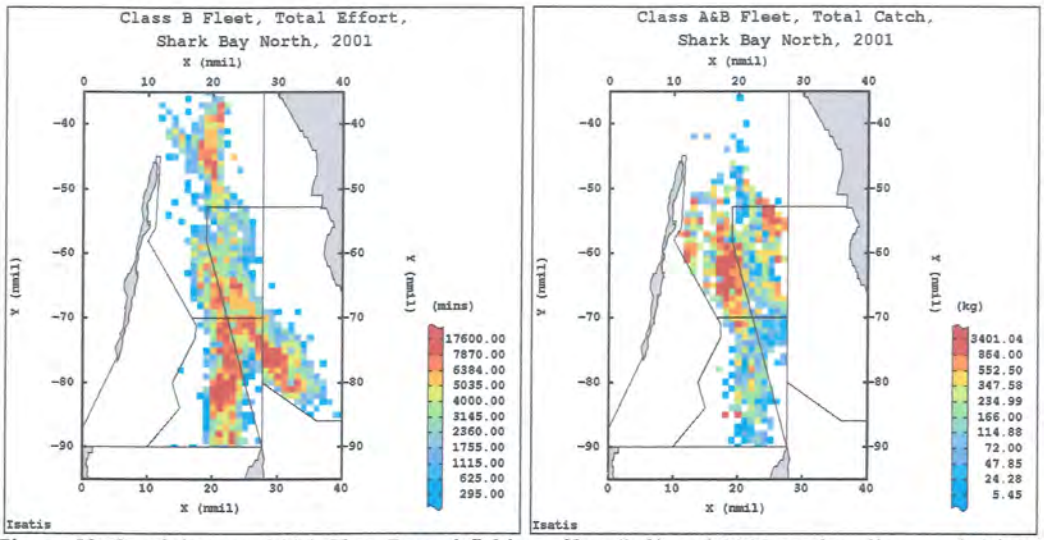

Figure 59: Spatial maps, 2001 Class B total fishing effort (left) and 2001 total scallop catch (right)

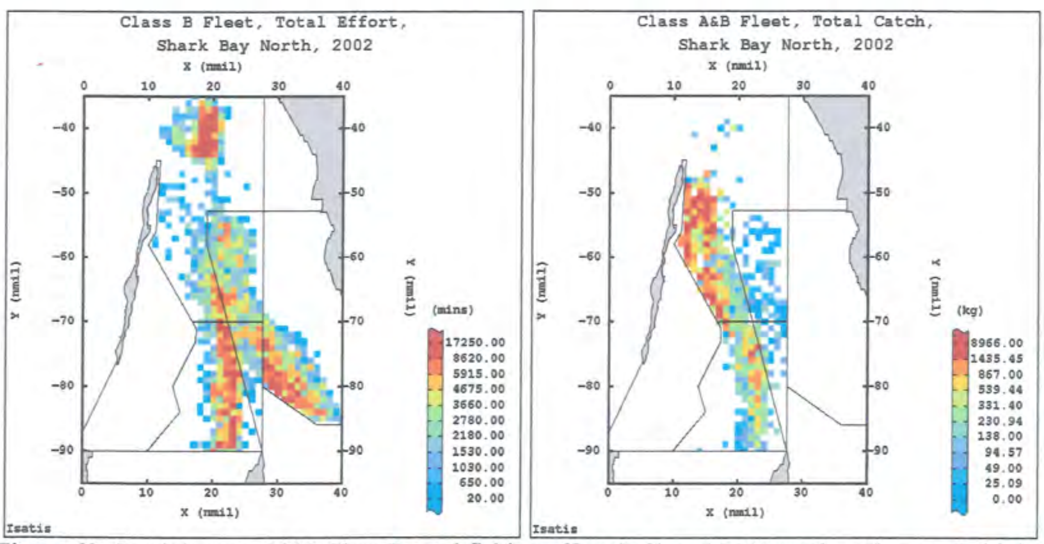

Figure 60: Spatial maps, 2002 Class B total fishing effort (left) and 2002 total scallop catch (right)

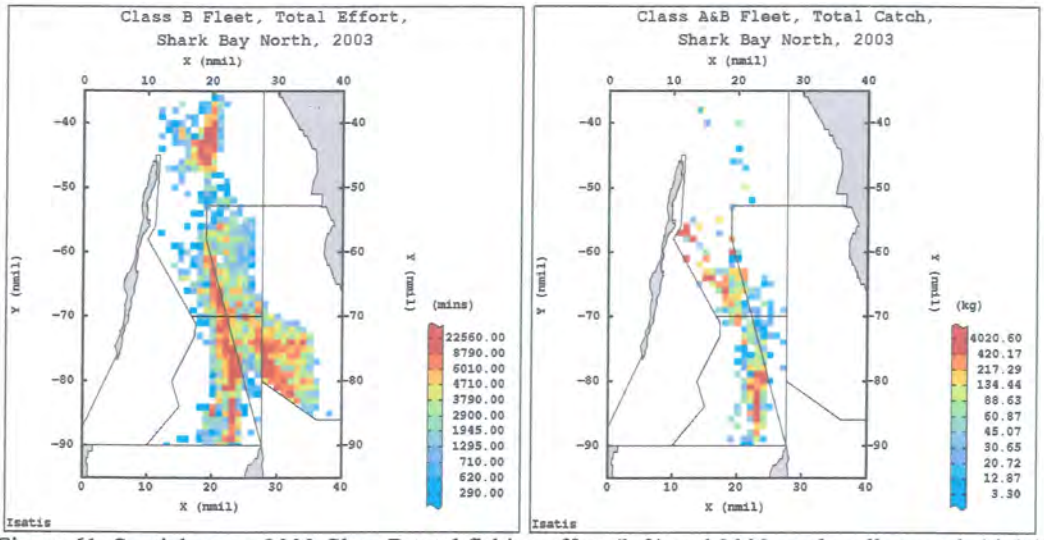

Figure 61: Spatial maps, 2003 Class B total fishing effort (left) and 2003 total scallop catch (right)

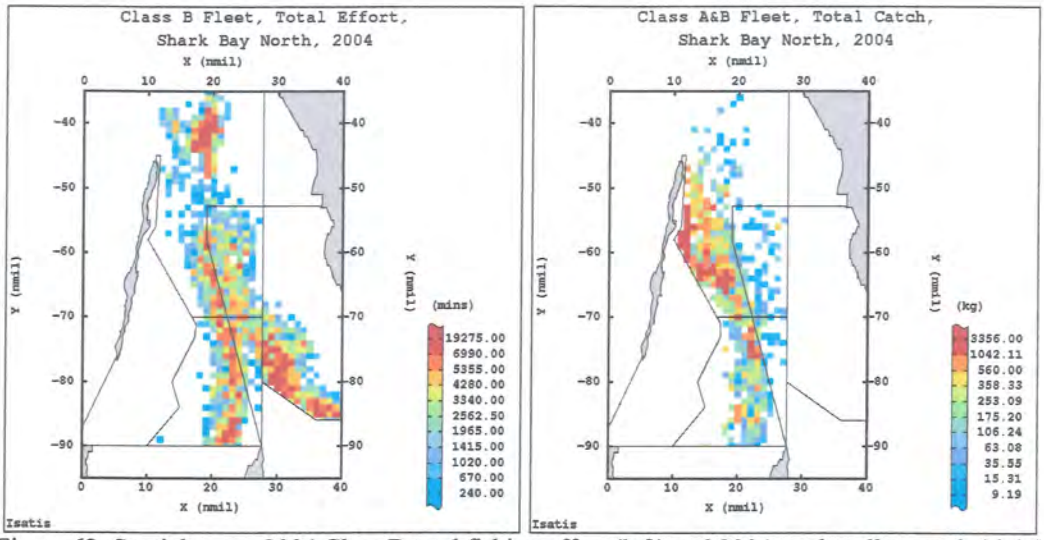

Figure 62: Spatial maps, 2004 Class B total fishing effort (left) and 2004 total scallop catch (right)

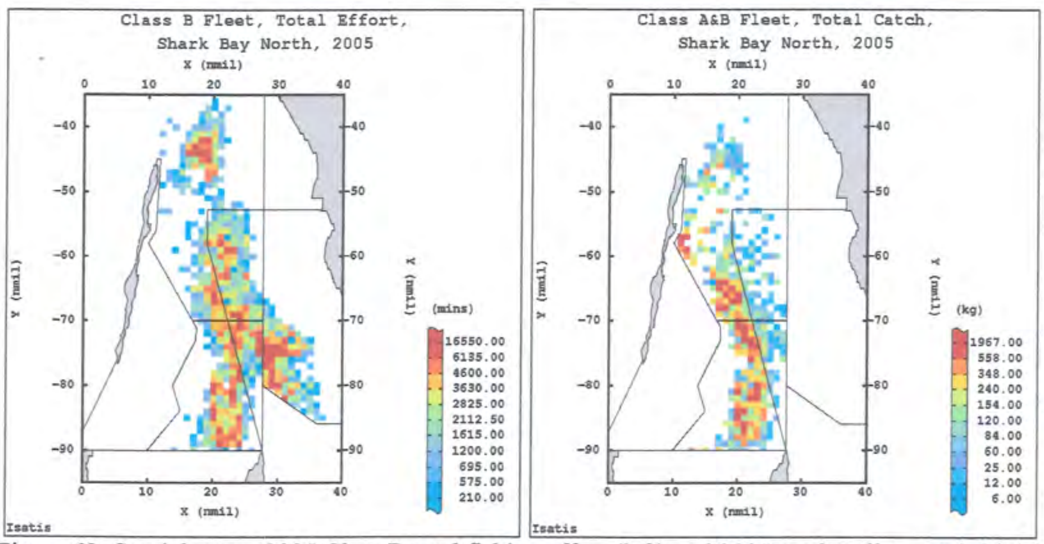

Figure 63: Spatial maps, 2005 Class B total fishing effort (left) and 2005 total scallop catch (right)

Spatial maps of the total Class B fleet fishing effort and the total scallop catch in Denham Sound for the subsequent season are displayed in Figure 64 to Figure 69. These show that the fishing effort of the Class B fleet is generally concentrated in the centre and northwest of Denham Sound, often at locations for which high scallop densities were predicted from the preceding survey data.

For the 2000 fishing season several of the locations with high total scallop catch also recorded a high Class B fleet effort. The maps of the 2001 season show an area of high Class B fleet effort in the west of the region which overlaps an area of high scallop catch. An area of high Class B fleet fishing effort for the 2002 season contains many locations for which a low scallop catch was recorded and numerous others for which a large catch was recorded. For the 2003 season areas of high Class B fleet effort in the northwest and west of the region contain a number of locations at which a relatively low total scallop catch was recorded. The maps for the 2004 season display many locations along the southwest boundary of the fishing region at which both a high Class B fleet effort and a relatively low scallop catch were recorded. During this season however an area of high Class B fleet effort, recorded in the northwest of the region, contains many locations with a high total scallop catch. For the 2003 season many locations along the southwest boundary of the fishing region contain high class B fleet effort values and moderate to low total scallop catch values. An area further to the northeast of this boundary, for which lower Class B fleet effort values were typically recorded, contains many locations for which a large total scallop catch was recorded. These maps show that for Denham Sound there are no marked patterns between Class B fleet effort and total scallop catch during the fishing seasons under consideration.

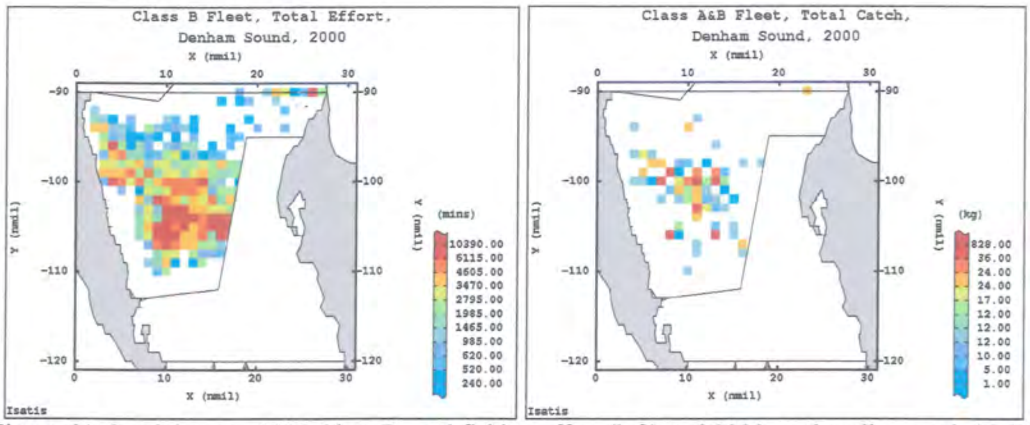

Figure 64: Spatial maps, 2000 Class B total fishing effort (left) and 2000 total scallop catch (right)

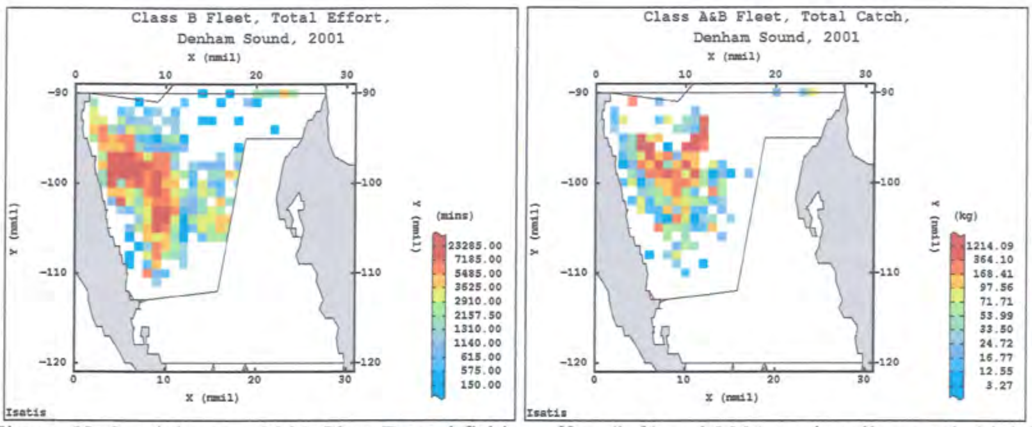

Figure 65: Spatial maps, 2001 Class B total fishing effort (left) and 2001 total scallop catch (right)

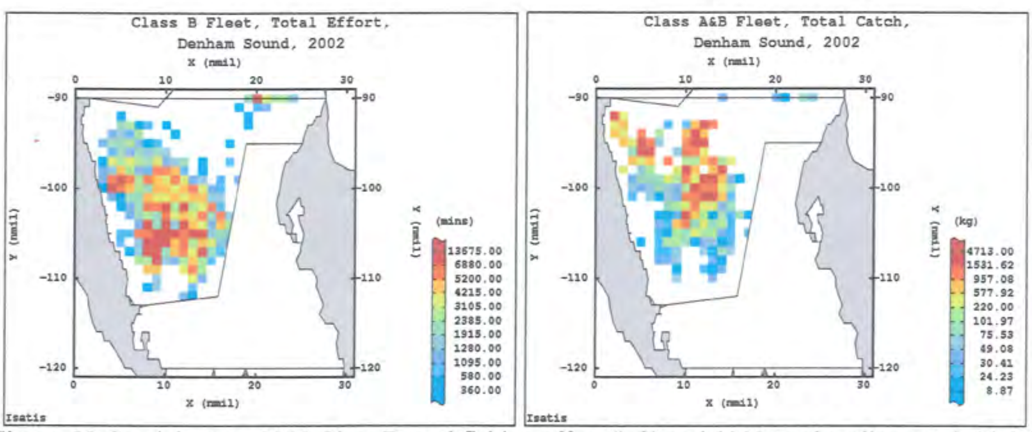

Figure 66: Spatial maps, 2002 Class B total fishing effort (left) and 2002 total scallop catch (right)

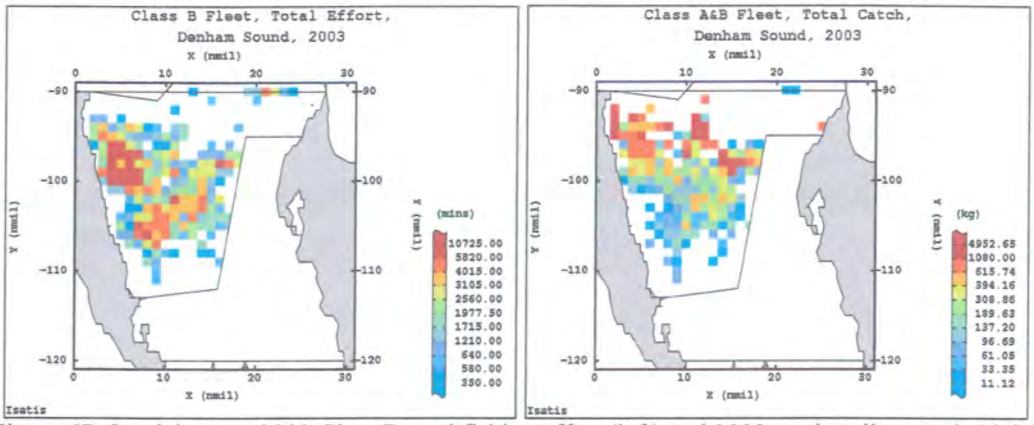

Figure 67: Spatial maps, 2003 Class B total fishing effort (left) and 2003 total scallop catch (right)

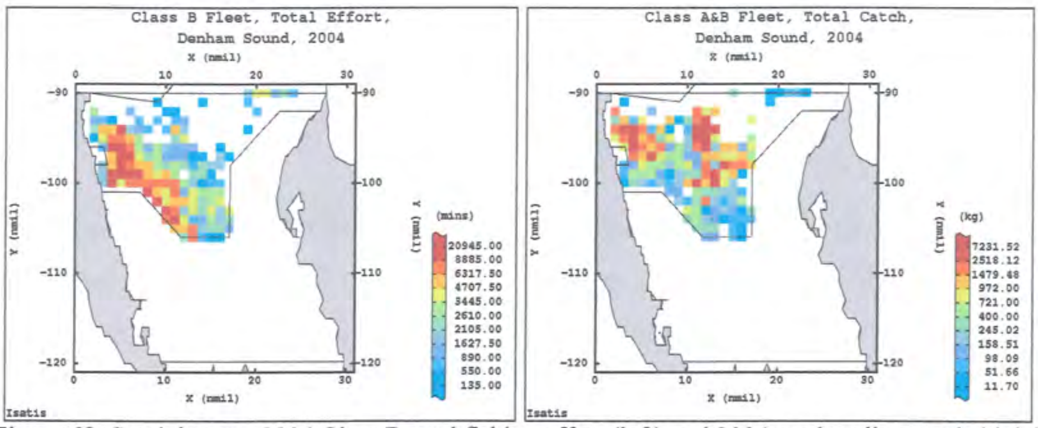

Figure 68: Spatial maps, 2004 Class B total fishing effort (left) and 2004 total scallop catch (right)

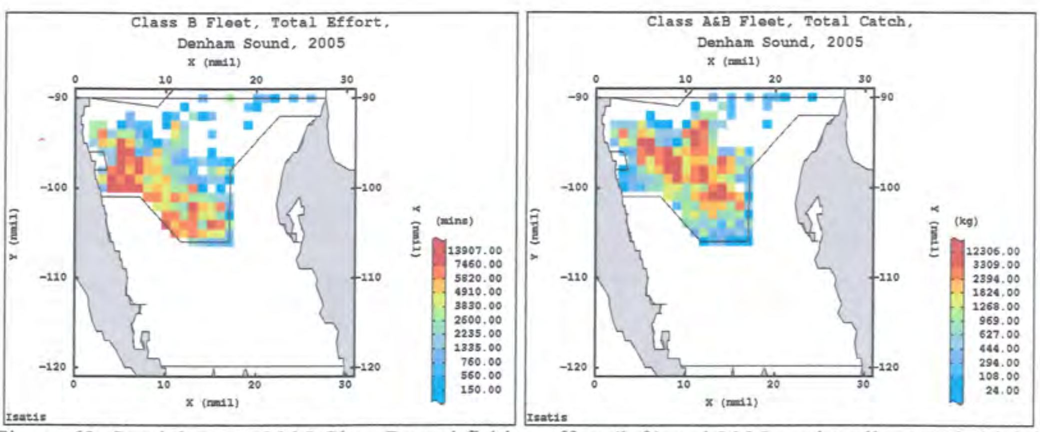

Figure 69: Spatial maps, 2005 Class B total fishing effort (left) and 2005 total scallop catch (right)

4.2. *Correlation Analysis*

4.2.1. Total Scallop Density Estimates and Combined Class A and B Total Scallop Catch

To better understand the relationship between the scallop density estimates calculated using the scallop survey results and the total scallop catch for the following fishing season correlation analysis has been carried out using data from locations at which these two variables were recorded. This analysis involves investigating scatter plots of the data and calculating correlation coefficients and has been conducted on the Shark Bay North and Denham Sound regions separately.

The data used for this analysis consists of the co-located total scallop density estimates and the total scallop catch of the Class A and Class B fleets combined. These common locations and the corresponding values of each variable are displayed in Figure 70 to Figure 75 for Shark Bay North and Figure 76 to Figure 81 for Denham Sound. These show that for both regions there are typically a large number of common locations for each season and that these locations span much of each fishing ground. For both regions the estimated total scallop density and the total scallop catch, for both fleets combined, display similar spatial patterns.

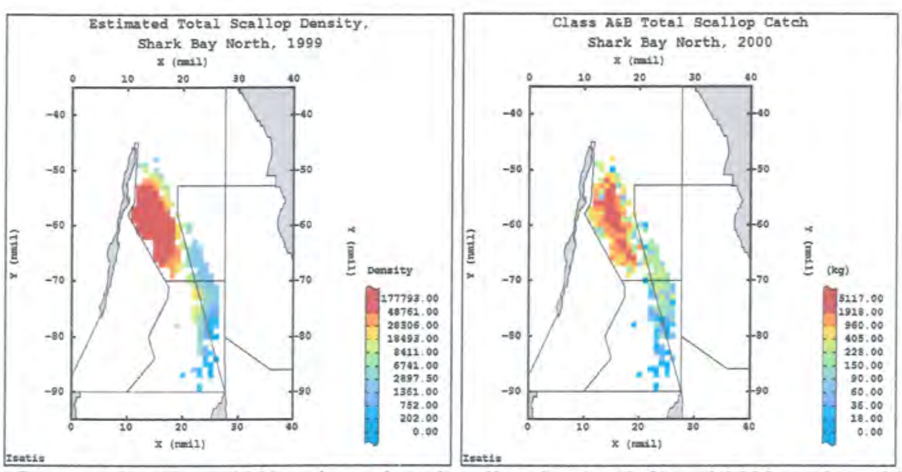

Figure 70: Common locations, 1999 estimated total scallop density (left) and 2000 total combined Class A and Class B scallop catch (right), Shark Bay North

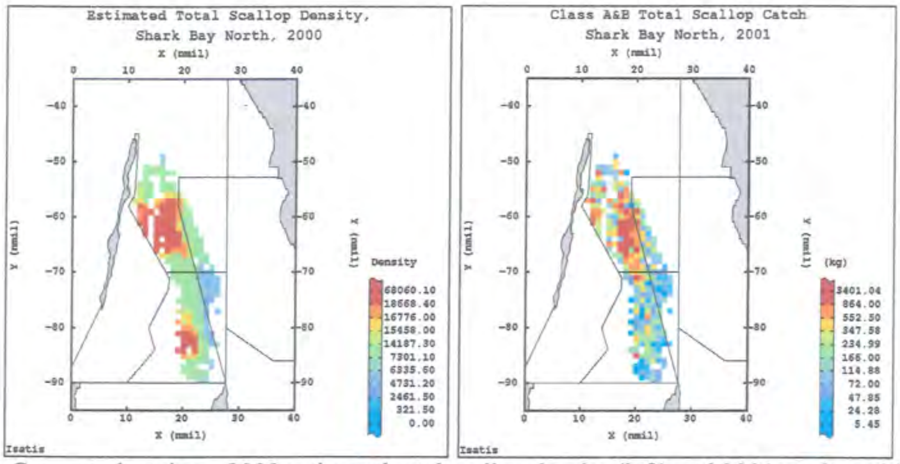

Figure 71: Common locations, 2000 estimated total scallop density (left) and 2001 total combined Class A and Class B scallop catch (right), Shark Bay North

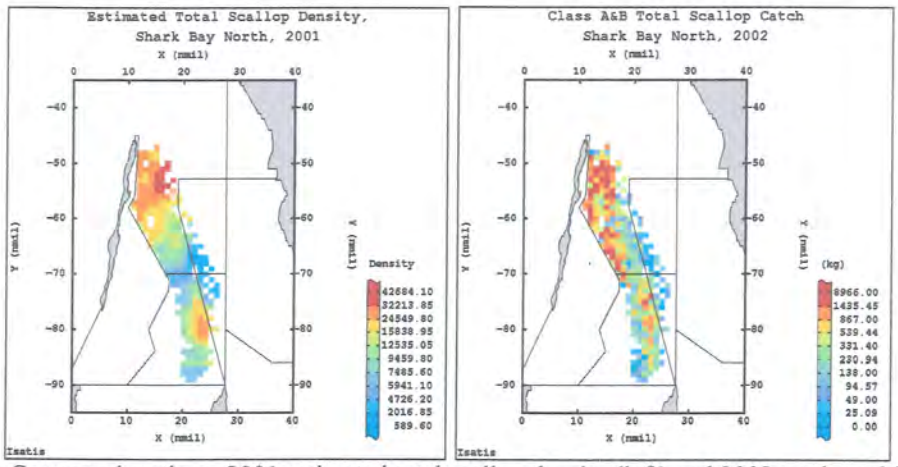

Figure 72: Common locations, 2001 estimated total scallop density (left) and 2002 total combined Class A and Class B scallop catch (right), Shark Bay North

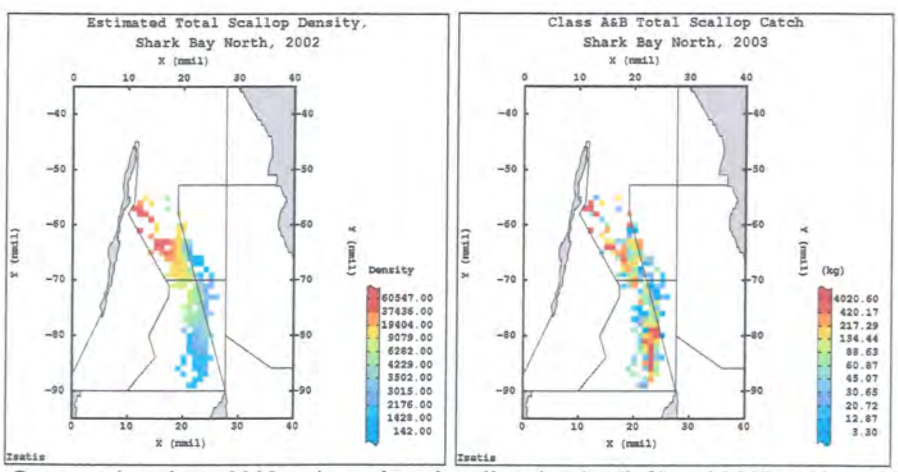

Figure 73: Common locations, 2002 estimated total scallop density (left) and 2003 total combined Class A and Class B scallop catch (right), Shark Bay North

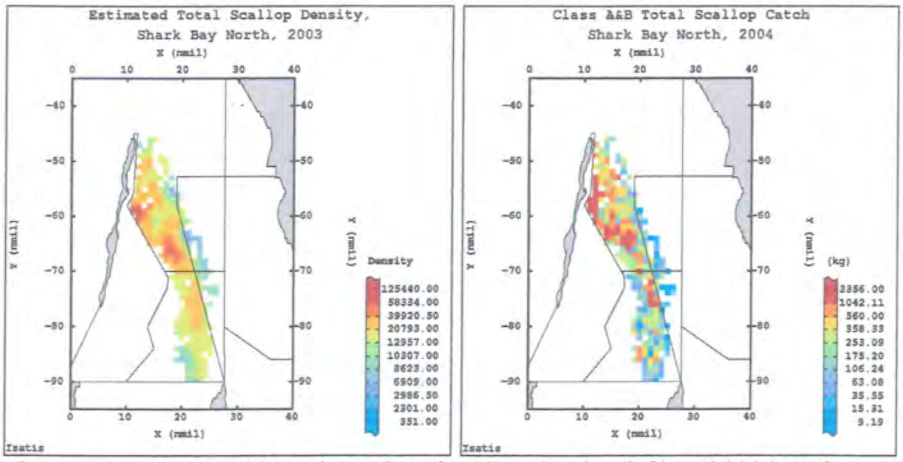

Figure 74: Common locations, 2003 estimated total scallop density (left) and 2004 total combined Class A and Class B scallop catch (right), Shark Bay North

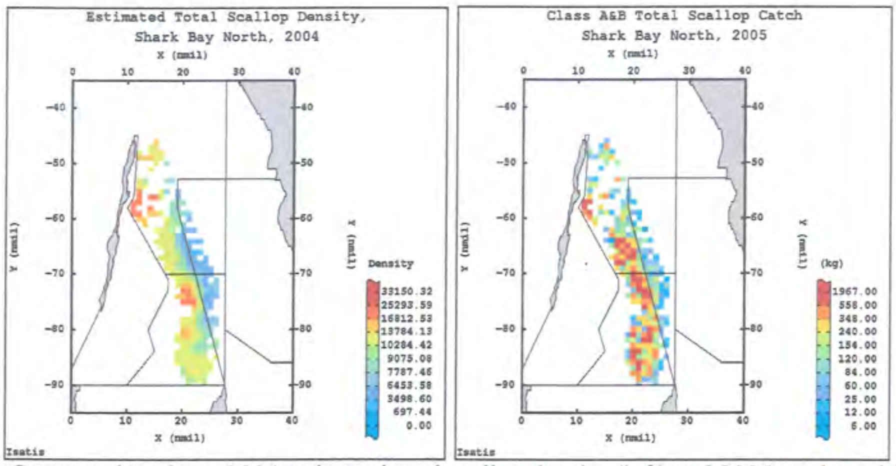

Figure 75: Common locations, 2004 estimated total scallop density (left) and 2005 total combined Class A and Class B scallop catch (right), Shark Bay North

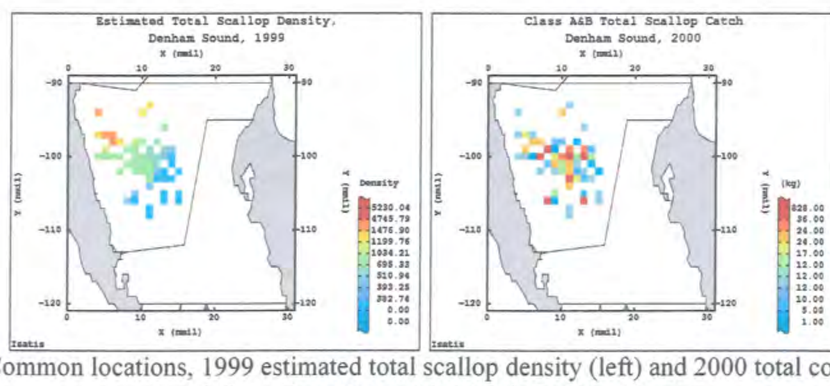

Figure 76: Common locations, 1999 estimated total scallop density (left) and 2000 total combined Class A and Class B scallop catch (right), Denham Sound

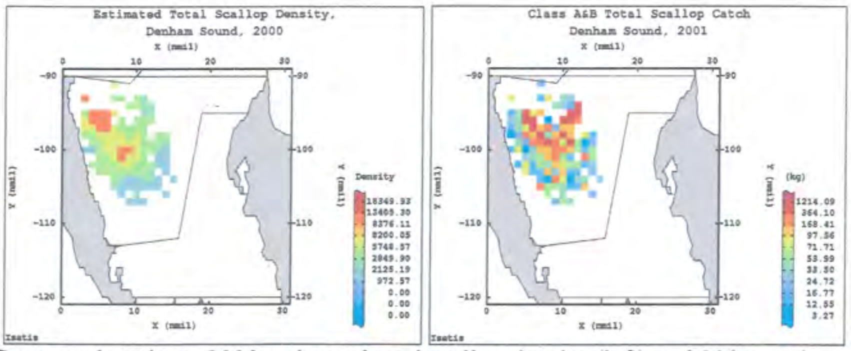

Figure 77: Common locations, 2000 estimated total scallop density (left) and 2001 total combined Class A and Class B scallop catch (right), Denham Sound

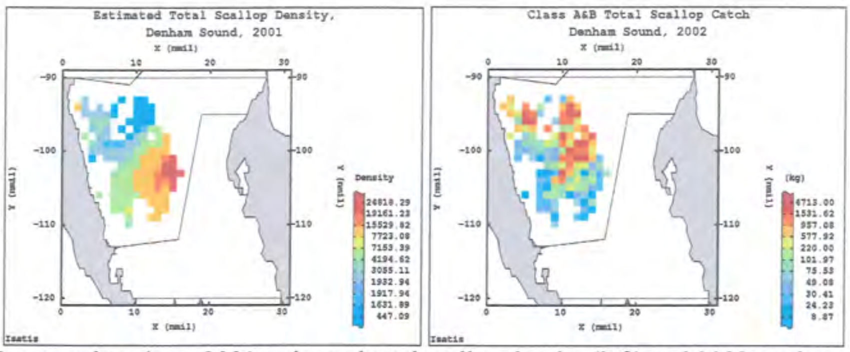

Figure 78: Common locations, 2001 estimated total scallop density (left) and 2002 total combined Class A and Class B scallop catch (right), Denham Sound

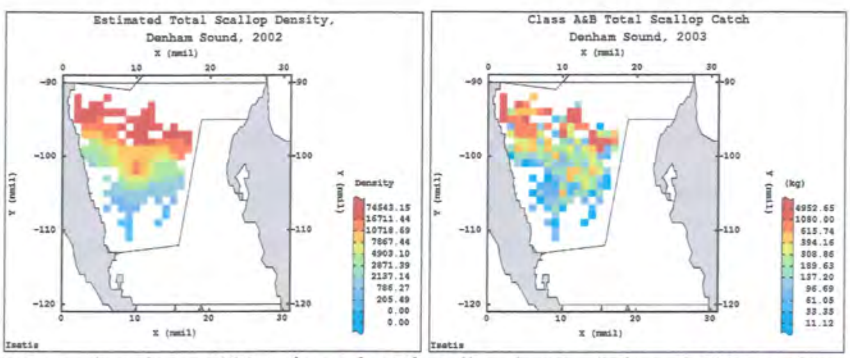

Figure 79: Common locations, 2002 estimated total scallop density (left) and 2003 total combined Class A and Class B scallop catch (right), Denham Sound

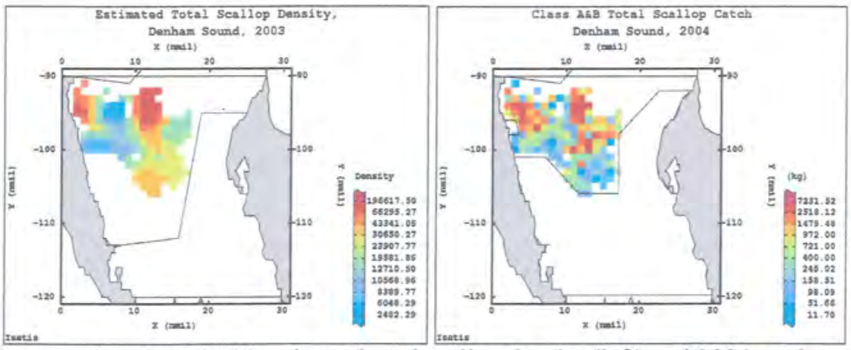

Figure 80: Common locations, 2003 estimated total scallop density (left) and 2004 total combined Class A and Class B scallop catch (right), Denham Sound

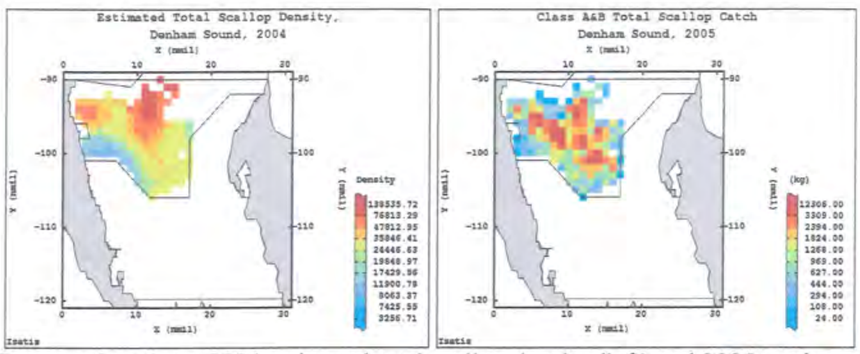

Figure 81: Common locations, 2004 estimated total scallop density (left) and 2005 total combined Class A and Class B scallop catch (right), Denham Sound

Scatter plots of the scallop density estimates against the total scallop catch recorded at the location of each estimate are displayed in Figure 82 for the Shark Bay North region. These show that for most seasons high total scallop catch has generally been recorded at locations for which high scallop densities were estimated from the previous survey. The 2001 fishing season appears to be the exception to this with most of the high total scallop catch values not recorded at locations with high estimated density. For every season however many of the locations at which high scallop densities were estimated recorded low total scallop catches in the following season.

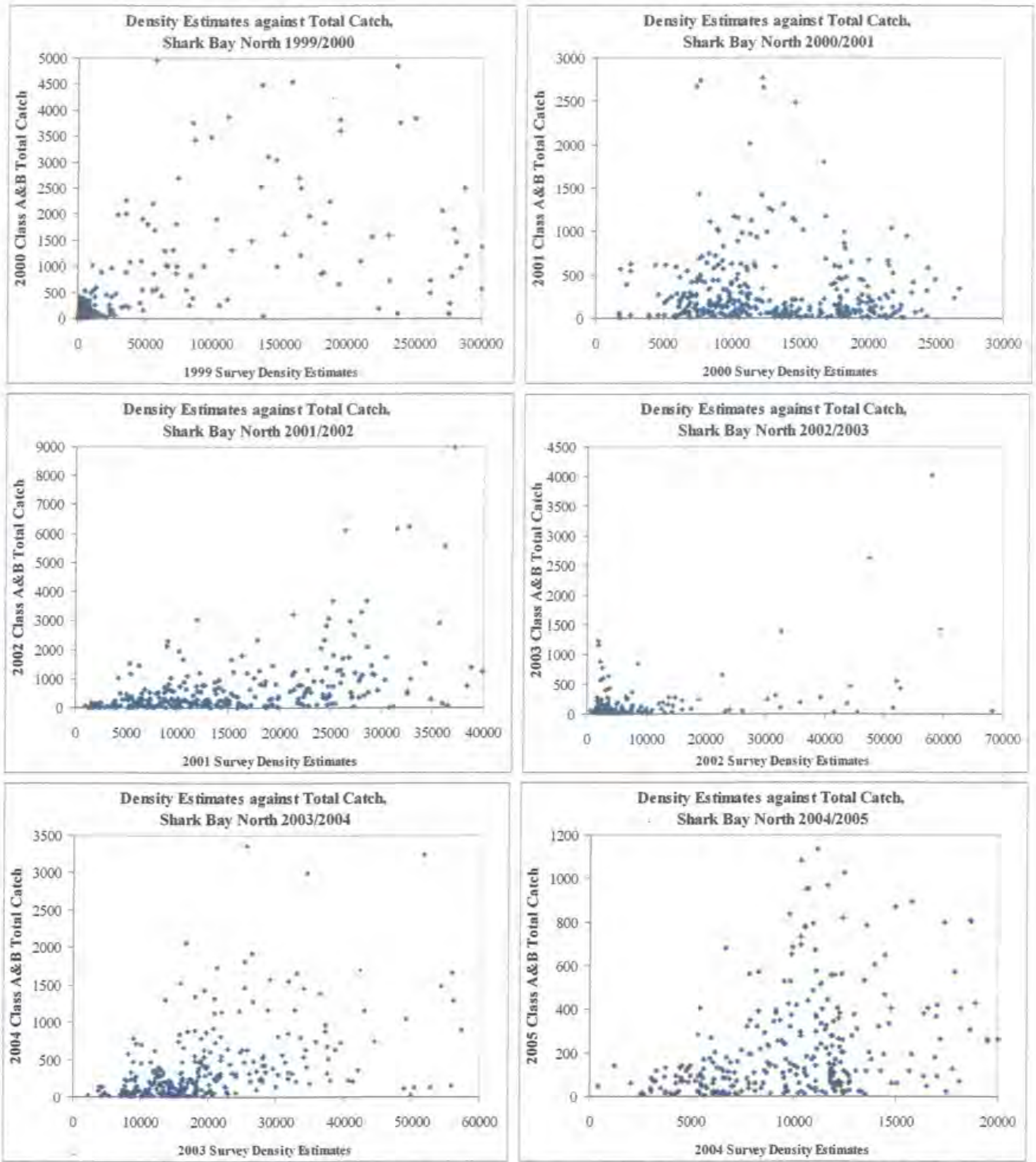

Figure 82: Scatter plots, scallop density estimates against total scallop catch, 2000 to 2005 fishing seasons Shark Bay North

Pearson's correlation coefficients and Spearman's rank correlation coefficients have been calculated to measure the strength of the linear correlation between the two variables under investigation for the Shark Bay North region. These coefficients are presented for each fishing season in Table 22. The Pearson's correlation coefficients reveal that for most fishing seasons there is a moderate positive linear correlation between the estimated scallop density and the total scallop catch for the following season. A somewhat weaker positive linear correlation is present between the density estimates and the total catch for the 2005 season as indicated by the Pearson's correlation coefficient. No linear correlation appears to be present between the two variables for the 2001 fishing season as these data have a Pearson's correlation very close to 0.

The Spearman's rank correlation coefficient indicates that there is a statistically significant moderate positive linear correlation between the ranks of the scallop density estimates and the total scallop catch for the 2000, 2002, 2004 and 2005 fishing seasons. The Spearman's correlation coefficients also suggest that there is weak linear correlation between the ranks of the two variables for the 2003 season and that there is a very weak negative linear correlation present in the 2001 season.

Table 22: Correlation Coefficients, scallop density estimates and total scallop catch, Shark Bay North

Shark Bay North				
Fishing	Pearson's	Spearman's Rank Correlation		
Season	Correlation	rho	Sig.(2-tailed)	Sig. at 0.05
2000	0.592	0.736	0.000	Yes
2001	-0.067	-0.100	0.080	No
2002	0.470	0.532	0.000	Yes
2003	0.436	0.210	0.009	Yes
2004	0.557	0.594	0.000	Yes
2005	0.398	0.402	0.000	Yes

Scatter plots of the scallop density estimates against the total scallop catch for the subsequent fishing season for Denham Sound are displayed in Figure 83. Unlike for the Shark Bay North region, locations at which large total scallop catch values were recorded do not appear to strongly correspond to locations at which a high scallop density was estimated. The 2003 season is an exception to this with many of the small total scallop catch values recorded at locations for which a low scallop density was estimated.

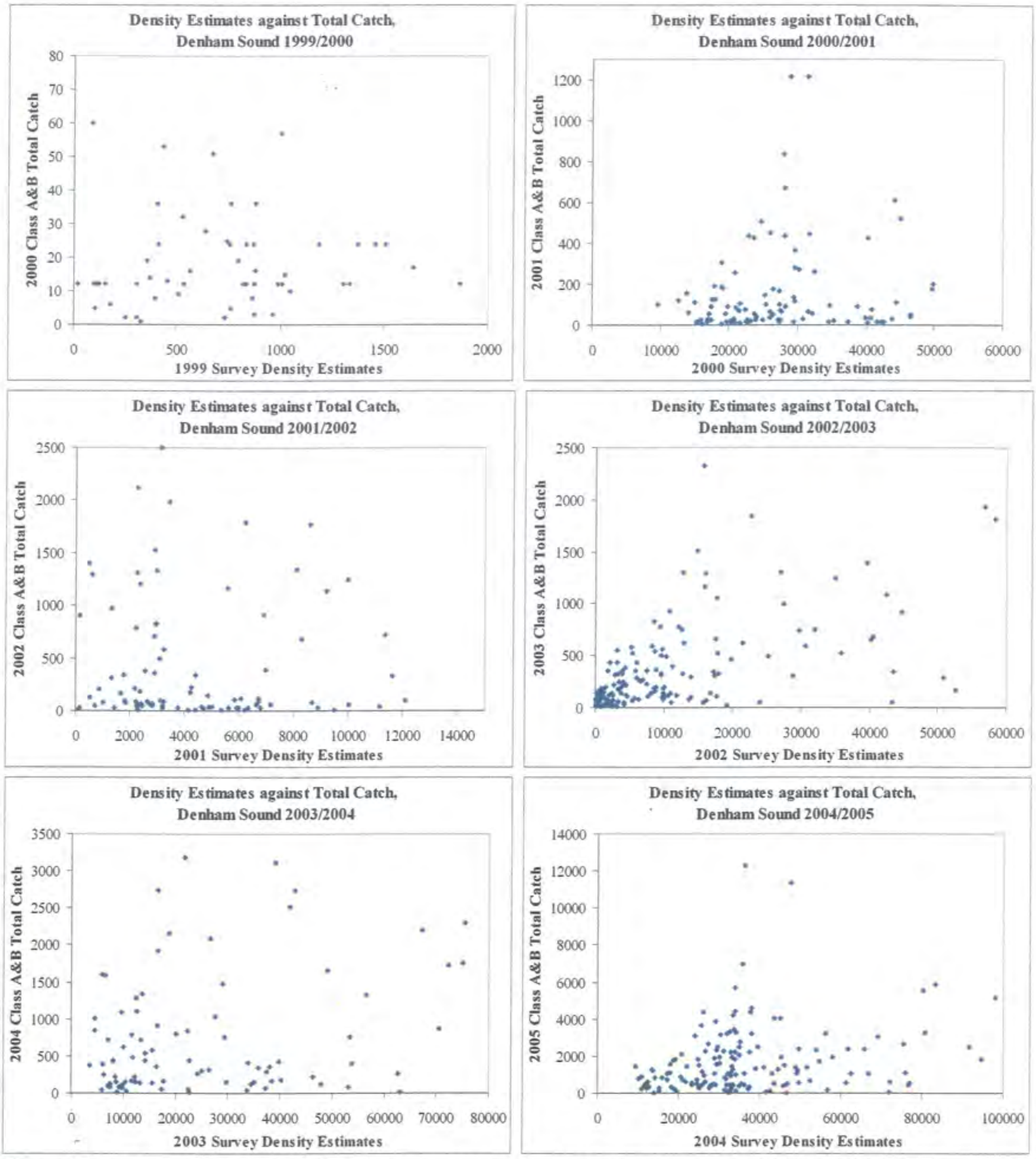

Figure 83: Scatter plots, scallop density estimates against total scallop catch, 2001 to 2005 fishing seasons Denham Sound

The Pearson's correlation coefficients calculated for the scallop density estimates and the total catch for Denham Sound (Table 23) reveal that for most seasons there is only a weak positive linear relationship between the two variables. For the 2003 and 2004 fishing season however there is a moderate positive linear relationship between the two variables as indicated by the Pearson's correlation coefficients. For the 2002 fishing season a weak negative linear correlation is present.

The Spearman's rank correlation coefficients also show that for most seasons there is only a weak positive linear correlation between the scallop density estimates and the total catch and that for the 2000 and 2001 fishing seasons this linear correlation is not statistically significant. For the 2002 season a weak negative linear correlation exists between the ranks for the total catch and density estimate data however it is not statistically significant. The Spearman's correlation coefficient for the 2003 season also indicates that there is a significant moderate linear correlation between the two variables for this season.

Table 23: Correlation Coefficients, density estimates and total scallop catch, Denham Sound

Denham Sound				
Fishing Season	**Pearson's Correlation**	**Spearman's Rank Correlation rho**	**Sig.(2-tailed)**	**Sig. at 0.05**
2000	0.019	0.159	0.245	No
2001	0.141	0.160	0.113	No
2002	-0.154	-0.138	0.117	No
2003	0.681	0.624	0.000	Yes
2004	0.551	0.267	0.001	Yes
2005	0.113	0.209	0.009	Yes

The scatter plots and correlation coefficients discussed above indicate that for the Shark Bay North region there is generally moderate positive correlation between the scallop density estimates, calculated from the pre-season scallop survey results, and the total scallop catch for the following season. For Denham Sound however there is typically only a weak linear relationship between the two variables apart from the 2003 season for which a moderate positive linear relationship is observed.

4.2.2. Scallop Density Estimates and Combined Class A and B Total Catch by Class B Total Fishing Effort

To further understand the relationship between the scallop density estimates calculated using the scallop survey results and the total scallop catch for the following fishing season the correlations between these variables have been analysed for separate categories of data determined by the magnitude of fishing effort recorded for the Class B fleet at each location. Locations that recorded a high total fishing effort for the Class B fleet were placed in the first category while those with a moderate total effort were allocated to a second category and locations with a low total effort were assigned to the third. Locations were deemed to have a high fishing effort if the total effort recorded at that location was above the 7th decile value and low if the total effort was below the 3rd decile value of the relevant fishing effort distribution, otherwise the location was deemed to have medium fishing effort. In addition to this the correlation between the density estimates and the total catch has been investigated separately for locations that were not fished by the Class B fleet.

The resulting correlation coefficients by effort are given in Table 24 and the corresponding scatter plots with fitted trendlines are shown Figure 84 to Figure 87.

Table 24: Pearson's correlation coefficients, combined Class A and B fleet total catch against density estimates by Class B fleet effort, Shark Bay North 2000 – 2005 fishing seasons
* indicates that the value is significant at the 0.05 level

	Shark Bay North			
Fishing Season	High Effort	Medium Effort	Low Effort	No Effort
2000	*0.469	0.162	0.093	*0.349
2001	-0.075	-0.026	-0.094	0.174
2002	*0.561	-0.048	*0.579	0.059
2003	*-0.401	*0.513	*0.562	*0.548
2004	*0.682	*0.596	*0.460	*0.412
2005	*0.608	*0.515	*0.331	*0.383

For the Shark Bay North region there does not appear to be any marked pattern between the level of Class B fishing effort and the strength of the linear correlation between the total catch and the density estimates. However, in general the degree of correlation is higher in later seasons with statistically significant correlations for seasons 2003 to 2005 irrespective of the effort type. Season 2004 shows the best linear correlation between survey prediction and actual catch for medium and high class B effort. For low and no effort, 2003 was the year with the highest correlation. For 2000, 2004 and 2005 the strength of linear correlation was highest for the high effort category. The season with the overall weakest correlation is 2001. Locations without any Class B effort have a positive linear trend while the remaining categories each have negative linear correlations. The corresponding Pearson's correlation coefficients in Table 24 reveal that the linear correlation for locations without Class B effort is very weak while for the remaining categories there is almost no linear correlation with coefficients close to 0. These results indicate that locations of high estimated scallop density tend to correspond with locations of high total scallop catch, for both fleet combined, regardless of the level of fishing effort used by the Class B fleet.

Except for the 2001 season there was a statistically significant linear relationship between estimates derived from the survey and catch at locations with high Class B effort. The scatter plots in Figure 84 show the quality of the trendline fitted for the data. For 2001 and 2003 there is a negative linear correlation, while in all other years the relation is positive.

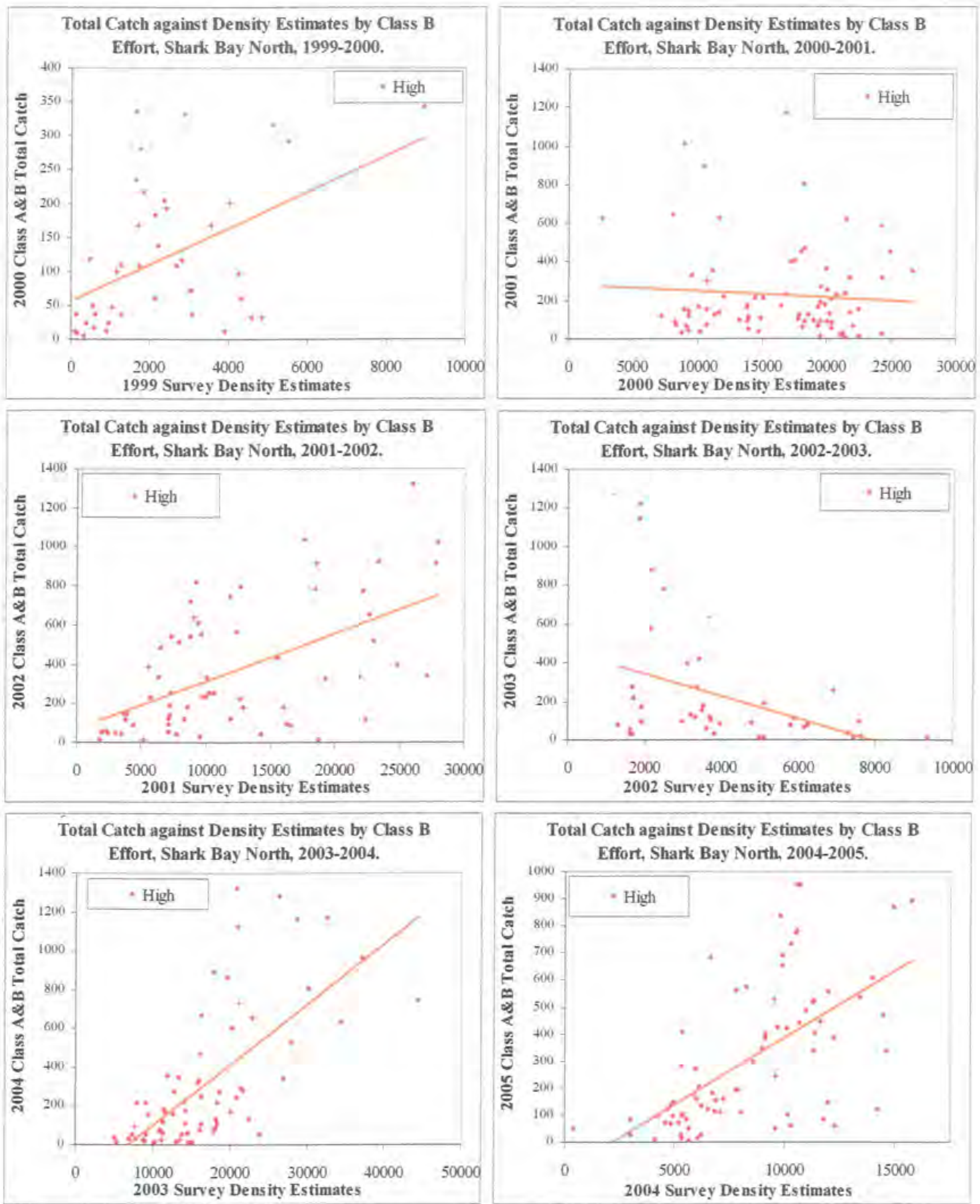

Figure 84: Scatter plots with fitted linear trend lines, Class A and B fleet total catch against density estimates by high Class B effort, Shark Bay North 2000-2005

For medium Class B effort there is typically a weak to moderate positive linear correlation, with 2004 showing the least dispersed cloud. For the 2003 to 2005 seasons this correlation is statistically significant at the 0.05 level.

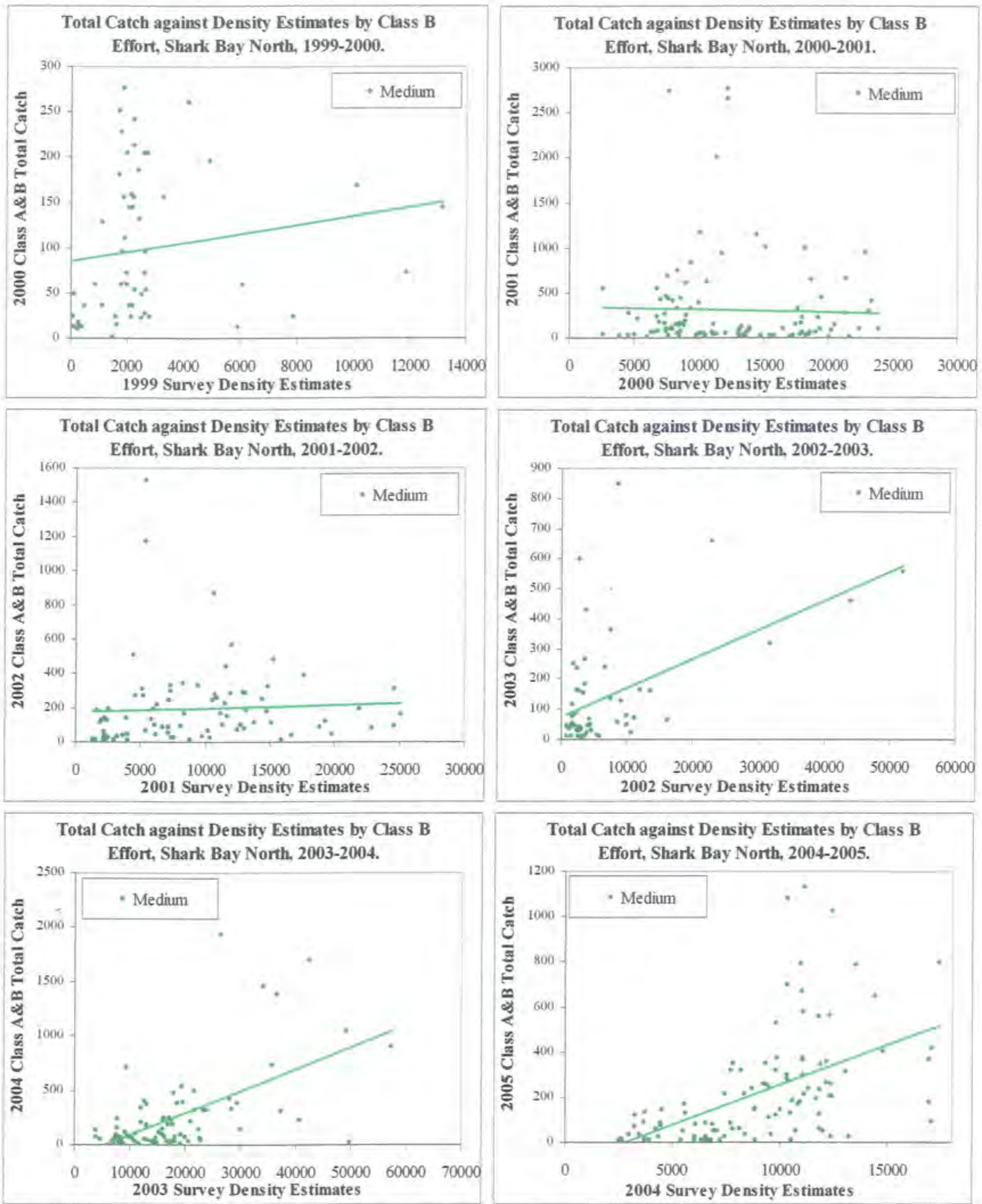

Figure 85: Scatter plots with fitted linear trend lines, Class A and B fleet total catch against density estimates by medium Class B effort, Shark Bay North 2000-2005

The most notable improvement in correlation between survey prediction and subsequent actual catch is for those locations with low Class B effort. While the correlation in 2000 and 2001 are negligible, there are statistically significant linear correlations between pre-season survey estimates and catch, see Figure 86 below.

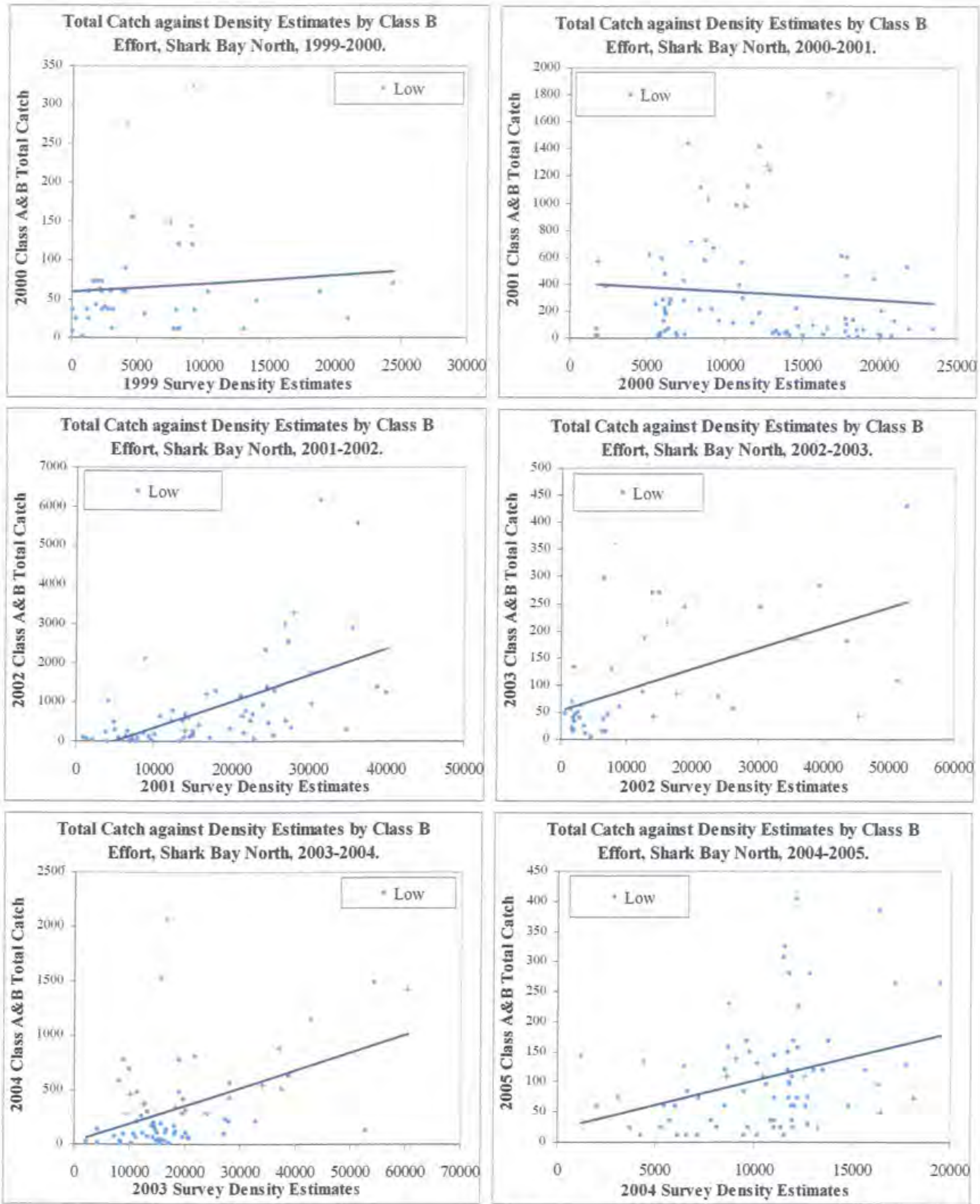

Figure 86: Scatter plots with fitted linear trend lines, Class A and B fleet total catch against density estimates by low Class B effort, Shark Bay North 2000-2005

The scatter plots for pre-season survey estimates against total catch at locations with no Class B effort are shown in Figure 87. The scatter is usually wide, with at best moderate linear correlation (see Table 24). The best linear correlation is that for the 2003 season, even though there are relatively few pairs it is significant at the 0.05 level.

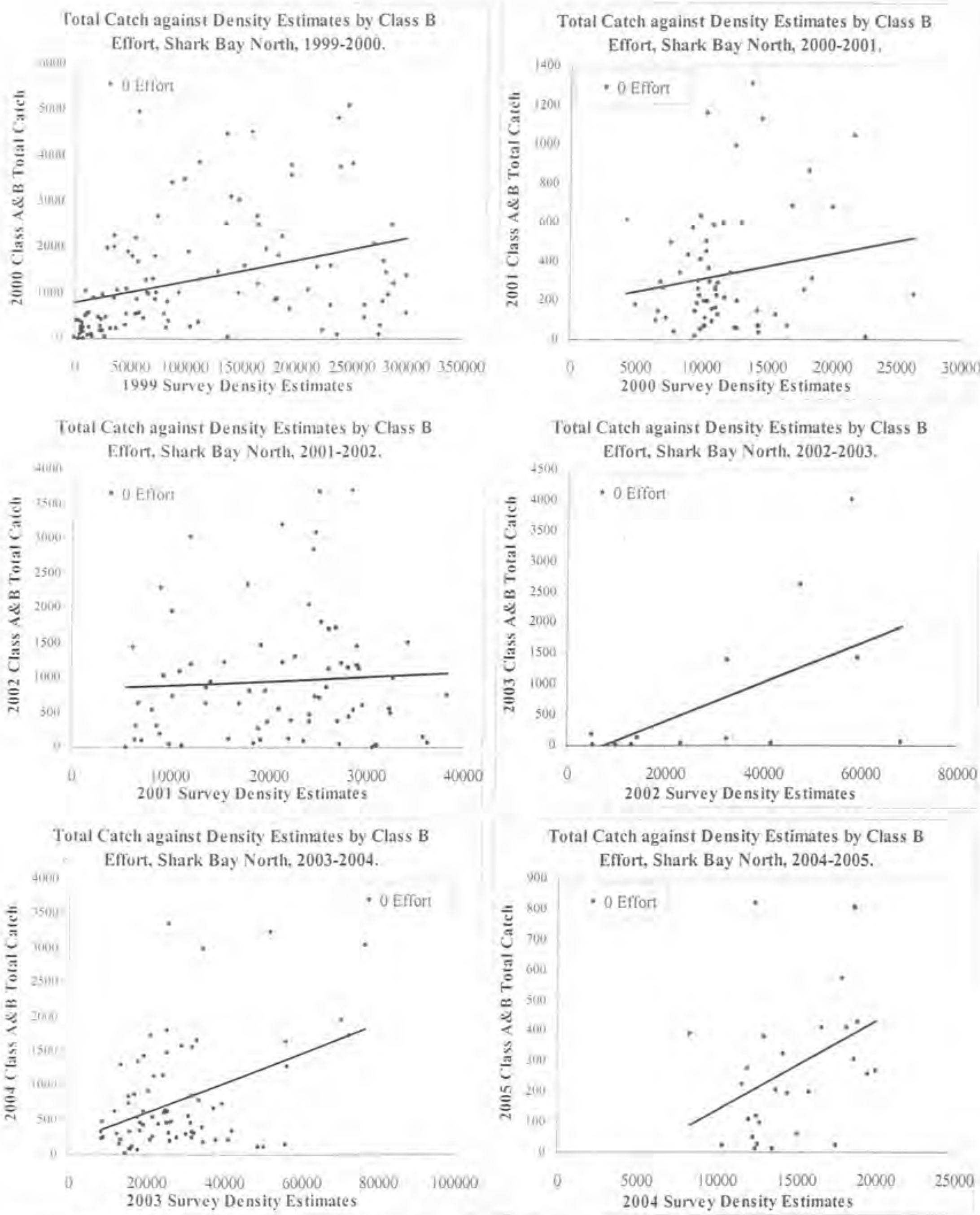

Figure 87: Scatter plots with fitted linear trend lines, Class A and B fleet total catch against density estimates by 0 Class B effort, Shark Bay North 2000-2005

The correlation coefficients of the relationship between the combined Class A and Class B fleet total catch and the density estimates by Class B fleet effort for Denham Sound are tabulated in Table 25. Although there are also no clear patterns present in the linear correlations between the total catch and density estimates across the effort categories for Denham Sound the strongest linear correlations are observed in the data for the 2003 and 2004 fishing seasons. As was the case with the Shark Bay North data there is no consistency in trend in particular for the 2000 to 2003 seasons with both negative and positive correlation coefficients coexisting in the same season. Subsequently, these correlation coefficients suggest that the level of fishing effort applied by the Class B fleet does not affect how well high estimated scallop density corresponds with high total scallop catch.

Table 25: Pearson's correlation coefficients, combined Class A and B fleet total catch against density estimates by Class B fleet effort, Denham Sound 2000 – 2005 fishing seasons
* indicates the value is significant at the 0.05 level

	Denham Sound			
Fishing Season	High Effort	Medium Effort	Low Effort	No Effort
2000	0.239	0.131	-0.048	N/A
2001	0.144	0.172	0.199	0.020
2002	-0.135	0.047	-0.177	-0.328
2003	*0.658	*0.300	*0.826	*0.578
2004	0.214	*0.742	*0.656	0.195
2005	*0.548	*0.405	*0.288	-0.232

The linear correlation between the scallop density estimates and the total scallop catch for both fleets combined at locations with a high Class B effort varies considerably across seasons with statistically significant positive linear correlation only observed in the data for the 2003 and 2005 seasons. The scatter plots in Figure 88 show that while there was a negative linear correlation for the 2002 season the data for each of the remaining seasons exhibit a positive linear correlation.

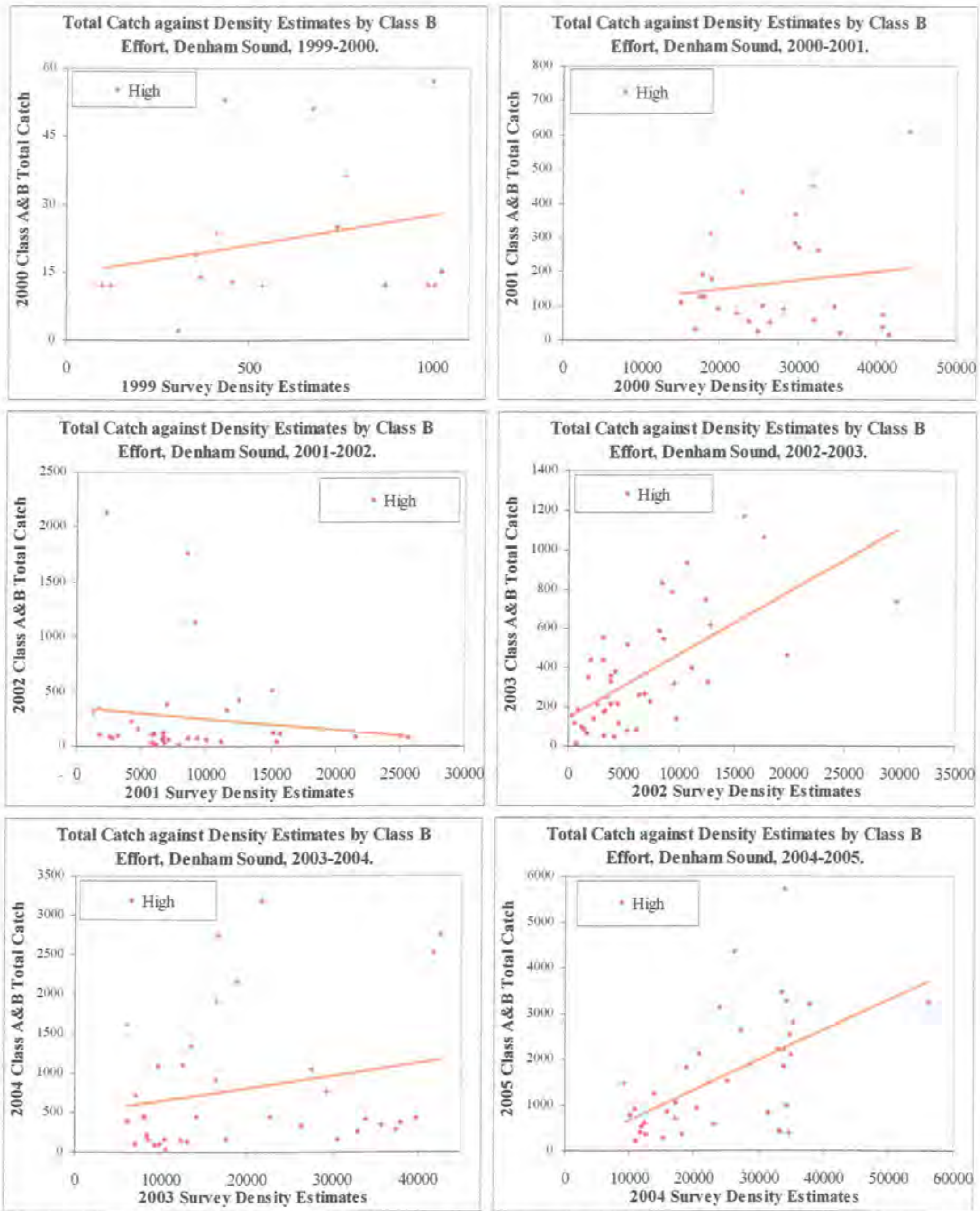

Figure 88: Scatter plots with fitted linear trend lines, Class A and B fleet total catch against density estimates by high Class B effort, Denham Sound 2000-2005

The scatter plots in Figure 89 illustrate that for each season there was a positive linear correlation between the scallop density estimates and the total catch achieved by both fleets combined at locations with a medium Class B effort. For the 2003 to 2005 seasons this linear correlation was statistically significant at the 0.05 level.

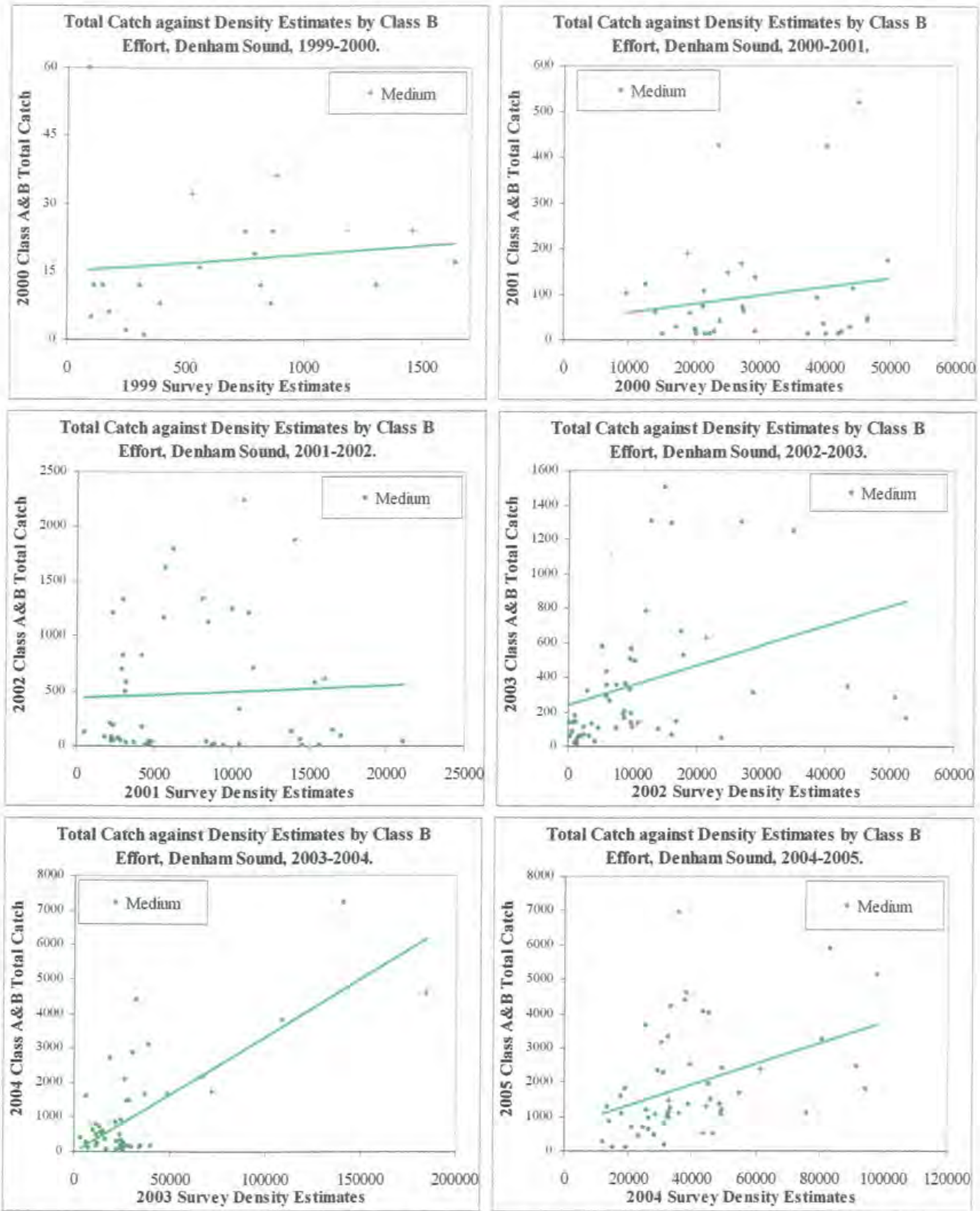

Figure 89: Scatter plots with fitted linear trend lines, Class A and B fleet total catch against density estimates by medium Class B effort, Denham Sound 2000-2005

At locations with a low Class B effort there was typically a positive linear correlation between the estimated scallop density and the total catch of the Class A and Class B fleets combined (Figure 90). For the 2003 to 2005 fishing seasons the positive linear correlation was statistically significant.

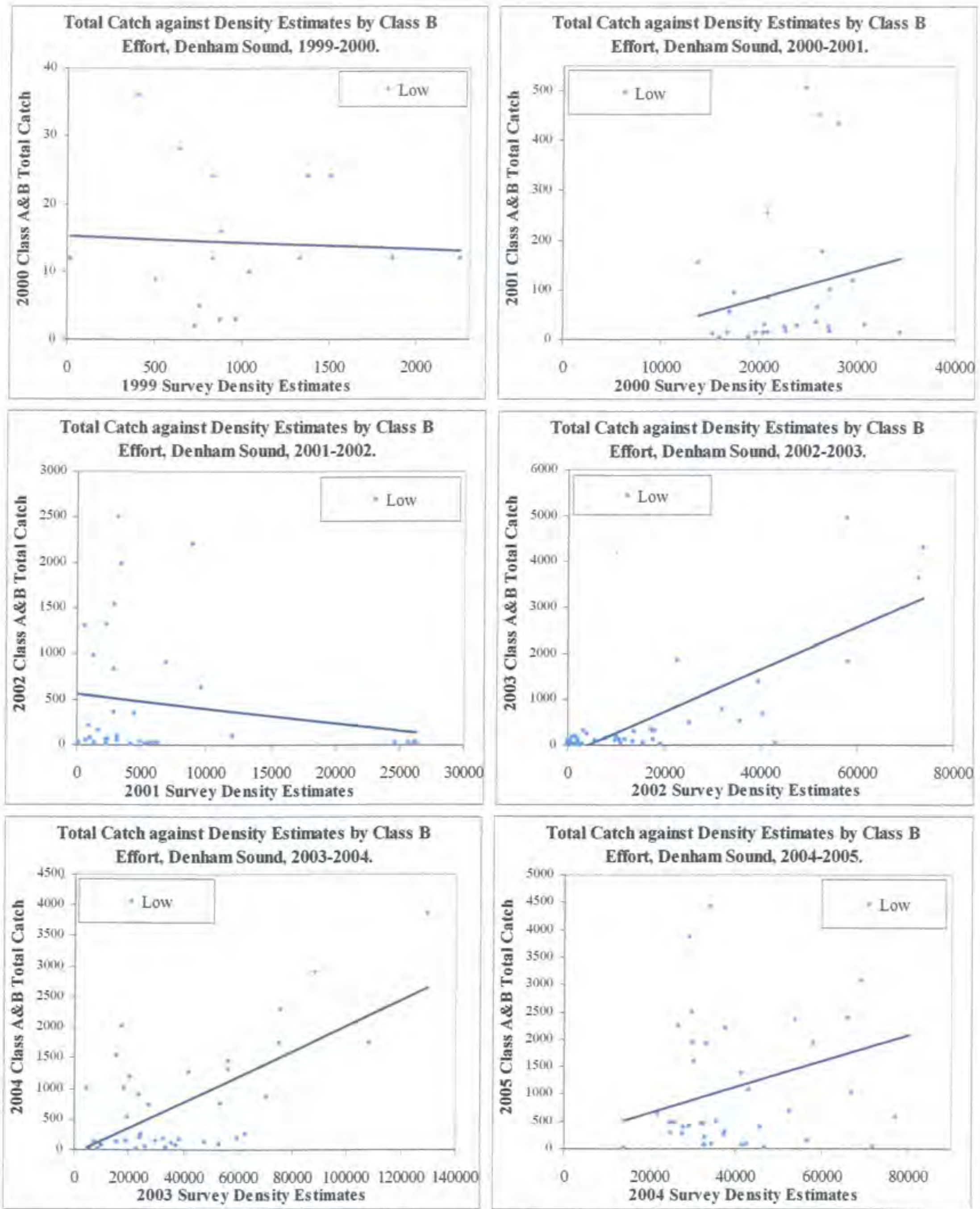

Figure 90: Scatter plots with fitted linear trend lines, Class A and B fleet total catch against density estimates by low Class B effort, Denham Sound 2000-2005

Scatter plots of scallop density estimates and the total scallop catch of both fleets combined at locations with no Class B effort are displayed in Figure 91. These plots show that there are relatively few data pairs for the 2001, 2002 and 2003 seasons. There are both positive and negative correlations for the data from this category with only the data for the 2003 season having a statistically significant (positive) linear correlation

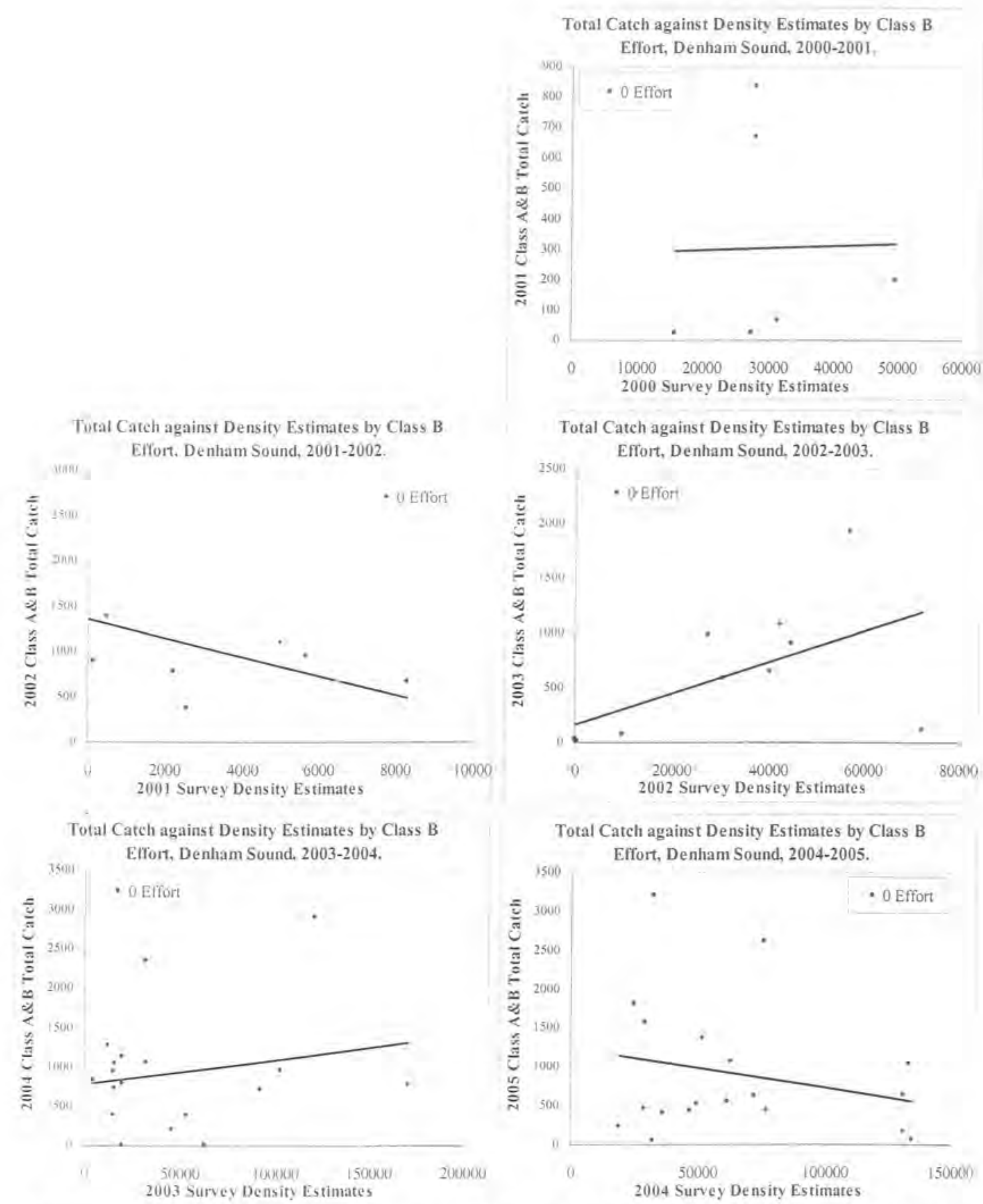

Figure 91: Scatter plots with fitted linear trend lines, Class A and B fleet total catch against density estimates by 0 Class B effort, Denham Sound 2000-2005

4.2.3. Scallop Density Estimates and Class A Total Catch by Class B Pre-Season Fishing Effort.

The correlation between the scallop density estimates, derived from the scallop survey, and the total catch of the Class A fleet has also been investigated. The linear correlation between these two variables has been measured separately for locations with different levels of pre-season Class B fishing effort. This has been done to gain a better understanding of the effect, if any, that the pre-season fishing effort of the Class B fleet has upon the scallop catch of the Class A fleet. In addition to the categories of effort used in the previous section (high, medium, low and no effort) a further category has been used in this analysis due to the low number of locations with recorded pre-season effort for some fishing seasons. This fifth category (> 0 Effort) consists of data recorded at locations for which some pre-season fishing effort has been recorded by the Class B fleet and is essentially a combination of the high, medium and low effort categories. The 2000, 2003 and 2005 fishing seasons for the Shark Bay North region and the 2000, 2004 and 2005 seasons for Denham Sound have not been analysed here as for each of these seasons there is not a sufficient number of locations which contain both Class A catch and Class B pre-season effort values.

Spatial maps of the locations with both an estimated total scallop density and a Class A scallop catch value, for the following season, are displayed in Figure 92 to Figure 100 by region and fishing season. For Denham Sound, only the maps containing data for the 2001, 2002 and 2003 fishing season have been presented as no scallop catch for the Class A fleet was located in Denham Sound during the 2000 season and no pre-season fishing effort was used by the Class B fleet in this region during the 2004 and 2005 seasons.

These maps show that the number of common locations for the Shark Bay North region varies considerably between seasons as does the position of these locations. While the Red Cliff fishing ground usually has a fair number of common locations NW Peron often has only a few if any. The exceptions to this are the 2002 and 2004 fishing seasons for which the NW Peron fishing ground contains many common locations. The maps for Denham Sound show that the number of common locations in this region also differs noticeably between seasons and that they are mostly located in the northern half of the region.

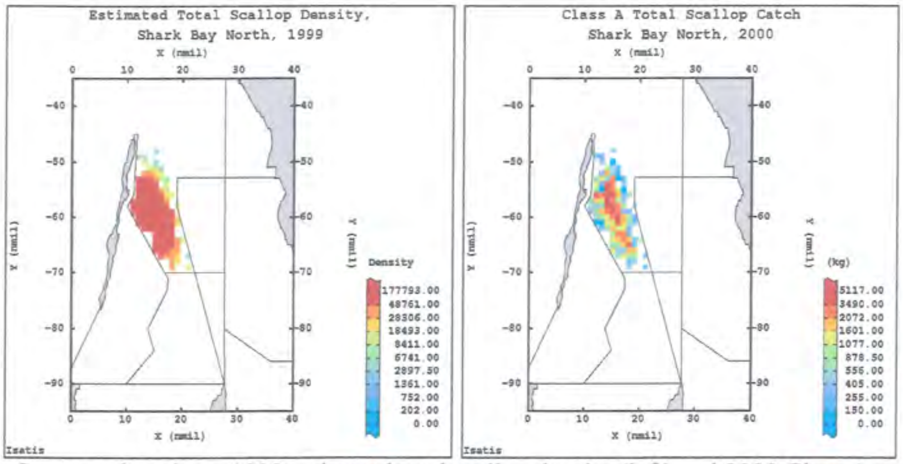

Figure 92: Common locations, 1999 estimated total scallop density (left) and 2000 Class A total scallop catch (right)

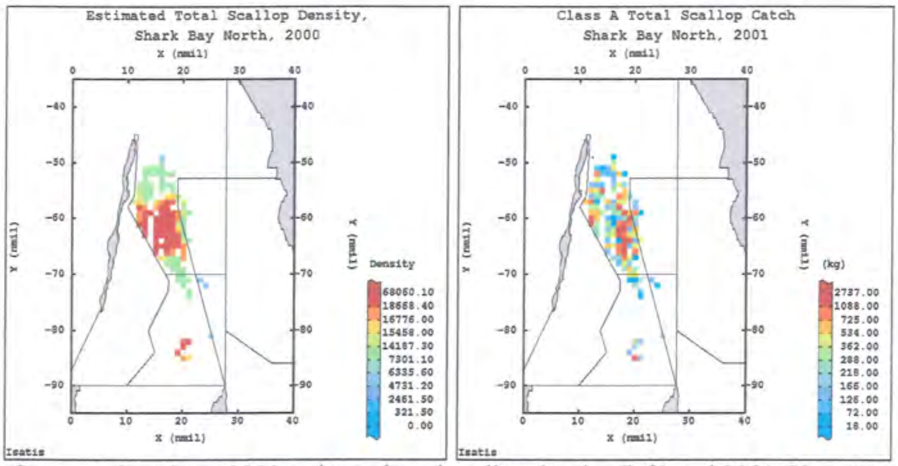

Figure 93: Common locations, 2000 estimated total scallop density (left) and 2001 Class A total scallop catch (right)

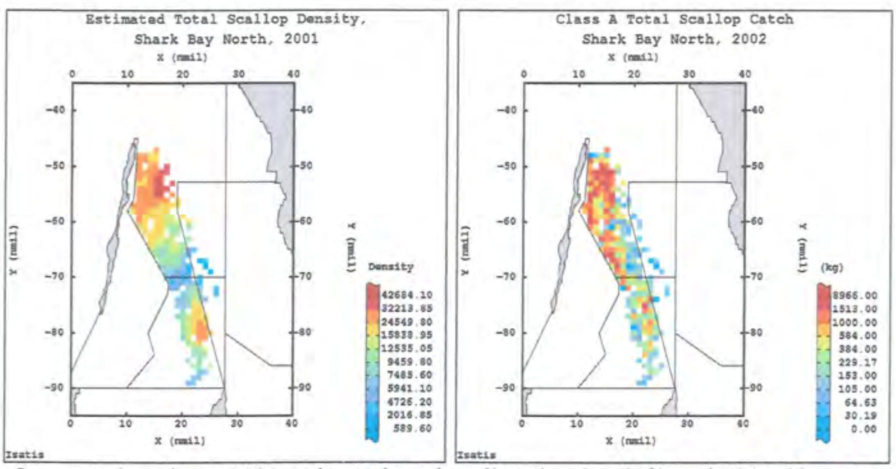

Figure 94: Common locations, 2001 estimated total scallop density (left) and 2002 Class A total scallop catch (right)

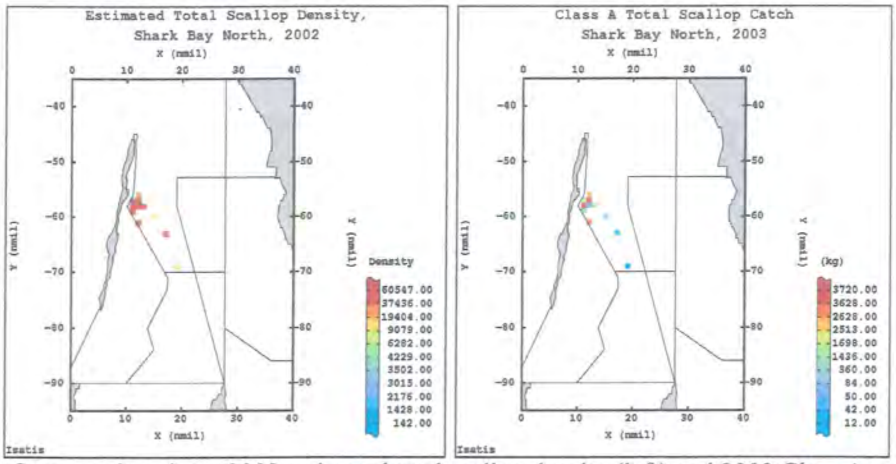

Figure 95: Common locations, 2002 estimated total scallop density (left) and 2003 Class A total scallop catch (right)

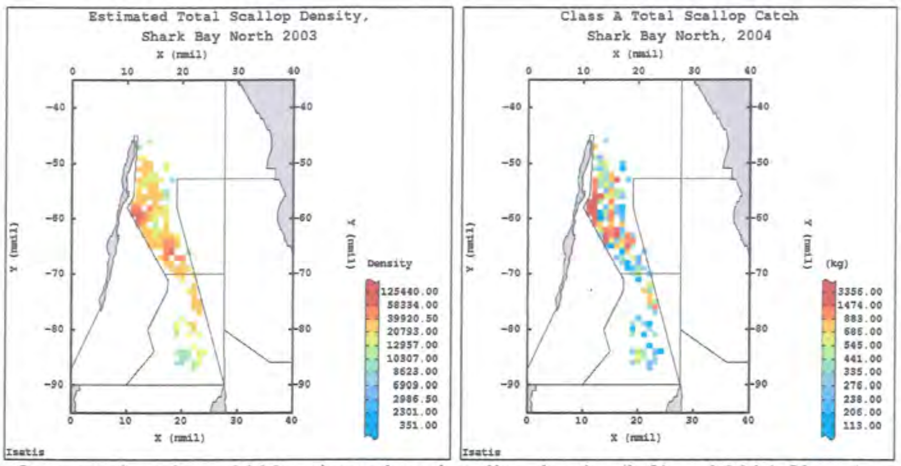

Figure 96: Common locations, 2003 estimated total scallop density (left) and 2004 Class A total scallop catch (right)

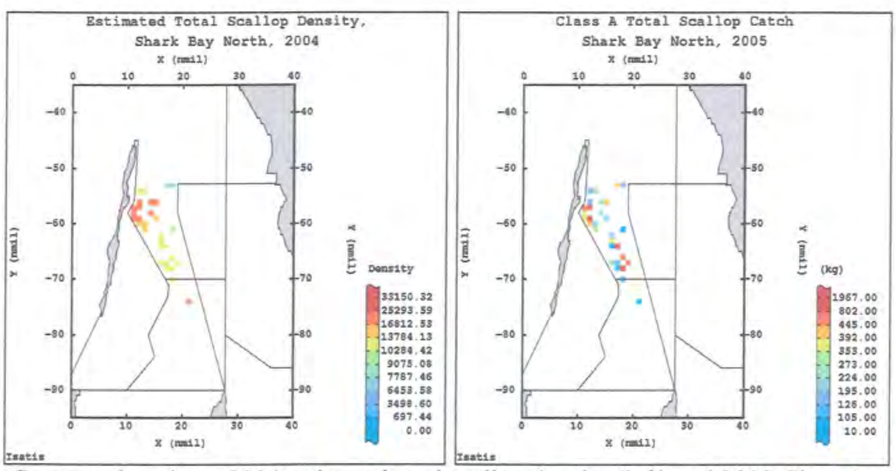

Figure 97: Common locations, 2004 estimated total scallop density (left) and 2005 Class A total scallop catch (right)

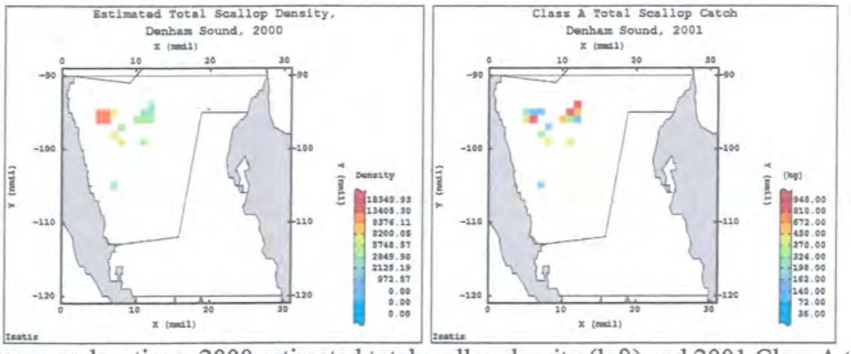

Figure 98: Common locations, 2000 estimated total scallop density (left) and 2001 Class A total scallop catch (right)

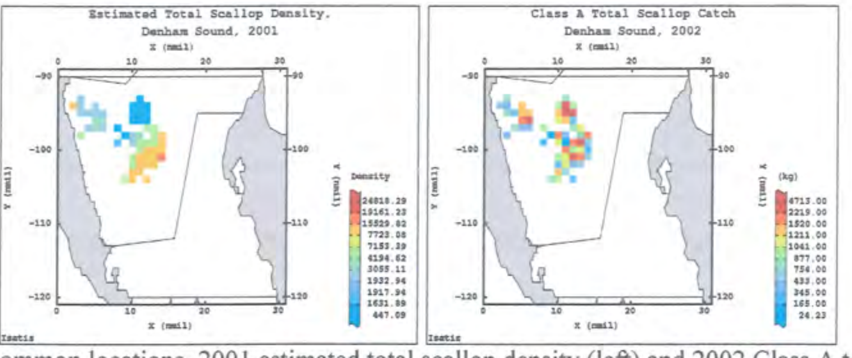

Figure 99: Common locations, 2001 estimated total scallop density (left) and 2002 Class A total scallop catch (right)

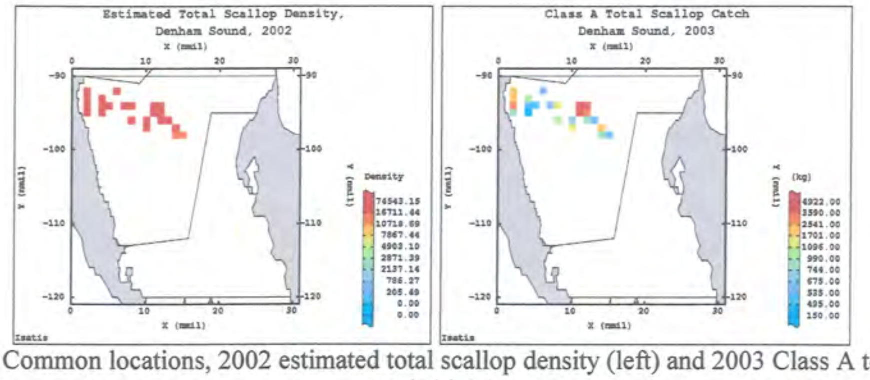

Figure 100: Common locations, 2002 estimated total scallop density (left) and 2003 Class A total scallop catch (right)

The correlation coefficients for the relationship between the estimated scallop density and the total catch achieved by the Class A fleet in Shark Bay North are given by effort in Table 26. The corresponding scatter plots, with fitted linear trendlines, are displayed in Figure 101 to Figure 105.

Table 26: Pearson's correlation coefficients, Class A fleet total catch against density estimates by Class B fleet pre-season effort, Shark Bay North
* indicates the value is significant at the 0.05 level

Shark Bay North					
Fishing Season	> 0 Effort	High Effort	Medium Effort	Low Effort	No Effort
2001	*0.275	0.545	0.235	0.453	*0.304
2002	*0.369	0.242	*0.585	*0.462	*0.378
2004	0.269	0.575	0.277	0.327	*0.378

A pattern emerges in the correlation between the total scallop catch for the Class A fleet and the density estimates with the positive linear correlation for >0 effort being somewhat weaker than that for the no effort category. The linear correlations for both of these categories are typically statistically significant and the difference between the strength of the correlation is quite small. No marked patterns are exhibited in the linear correlations of the high, medium and low effort categories. These results suggest that the level of Class B pre-season fishing effort does not have a substantial effect on how well high scallop density estimates correspond with high total scallop catch for the Class A fleet, nor does there appear to be an effect on the correspondence between low estimates and low catch.

The scatter plots in Figure 101 show that there is a positive linear correlation between the scallop density estimates and the total scallop catch of the Class A fleet for the >0 Class B pre-season effort category. For the 2001 and 2002 fishing seasons the linear correlation is statistically significant at the 0.05 level.

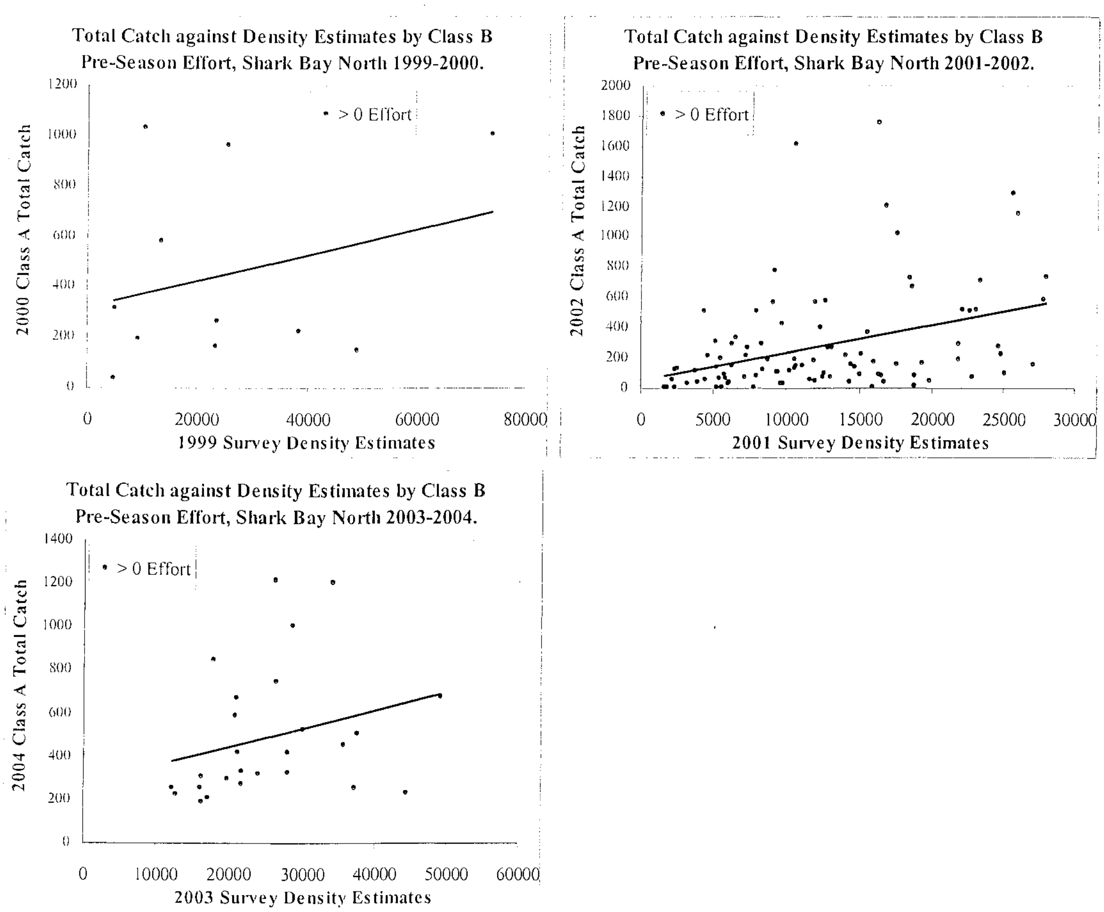

Figure 101: Scatter plots with fitted linear trend lines, Class A fleet total catch against density estimates by >0 Class B pre-season effort, Shark Bay North 2001, 2002 and 2004

For locations with a high Class B pre-season effort there is positive linear correlation between the scallop density estimates and the total catch of the Class A fleet for each season under consideration (Figure 102). In each case however this linear correlation is not statistically significant at the 0.05 level.

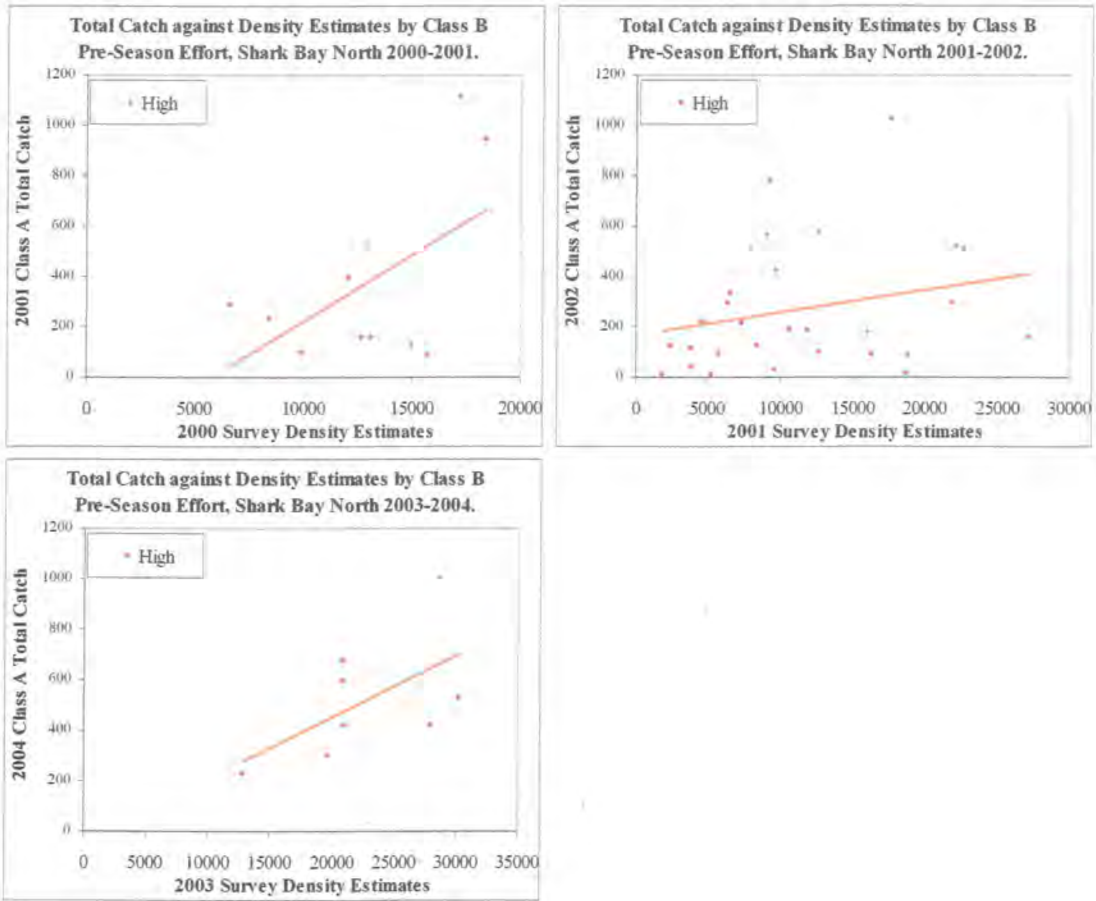

Figure 102: Scatter plots with fitted linear trend lines, Class A fleet total catch against density estimates by high Class B pre-season effort, Shark Bay North 2001, 2002 and 2004

Scatter plots of the scallop density estimates and the total scallop catch of the Class A fleet at locations with a medium Class B pre-season effort are displayed in Figure 103. For each season under consideration there is a positive linear correlation and for the 2002 season this correlation is statistically significant.

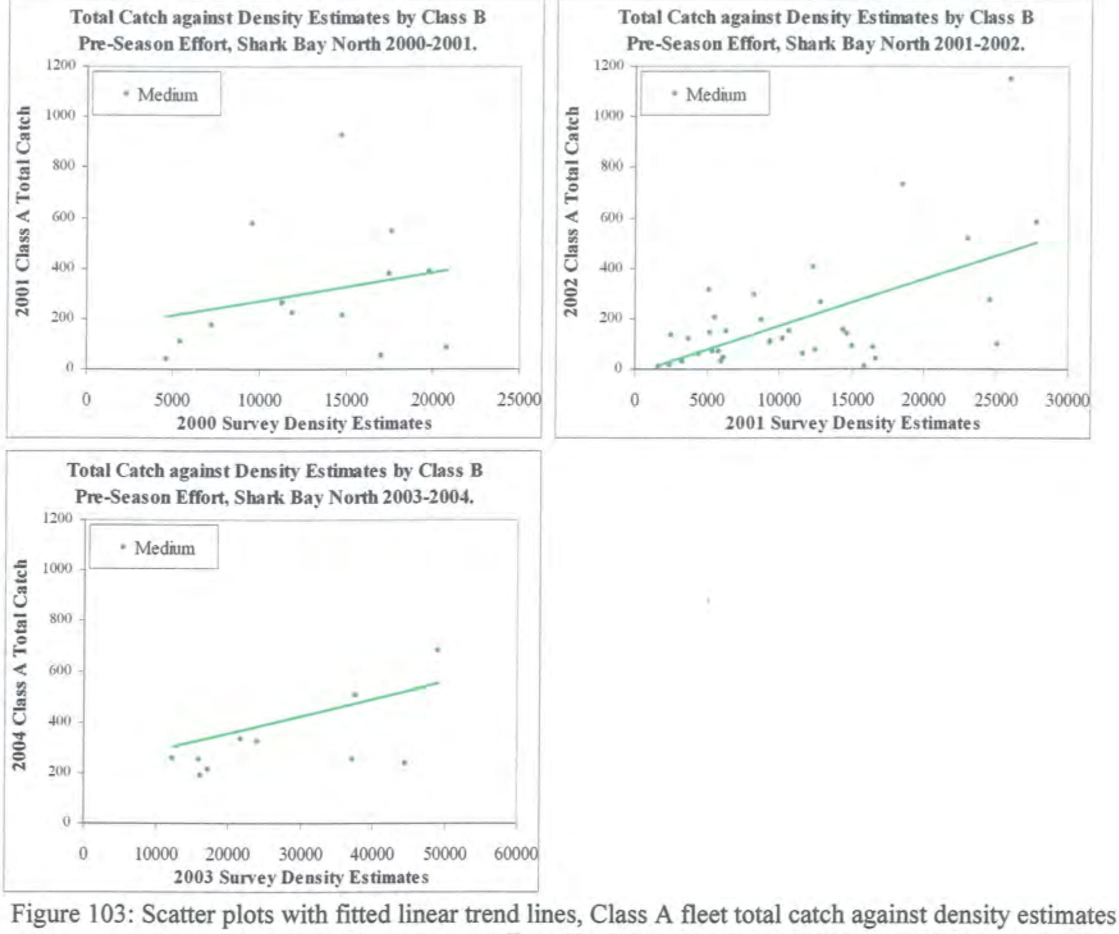

Figure 103: Scatter plots with fitted linear trend lines, Class A fleet total catch against density estimates by medium Class B pre-season effort, Shark Bay North 2001, 2002 and 2004

Scatter plots of the scallop survey data and the total catch of the Class A fleet at locations with a low Class B pre-season effort (Figure 104) reveal that for each case there is a positive linear correlation between the variables. This linear correlation however is only statistically significant for the 2002 season.

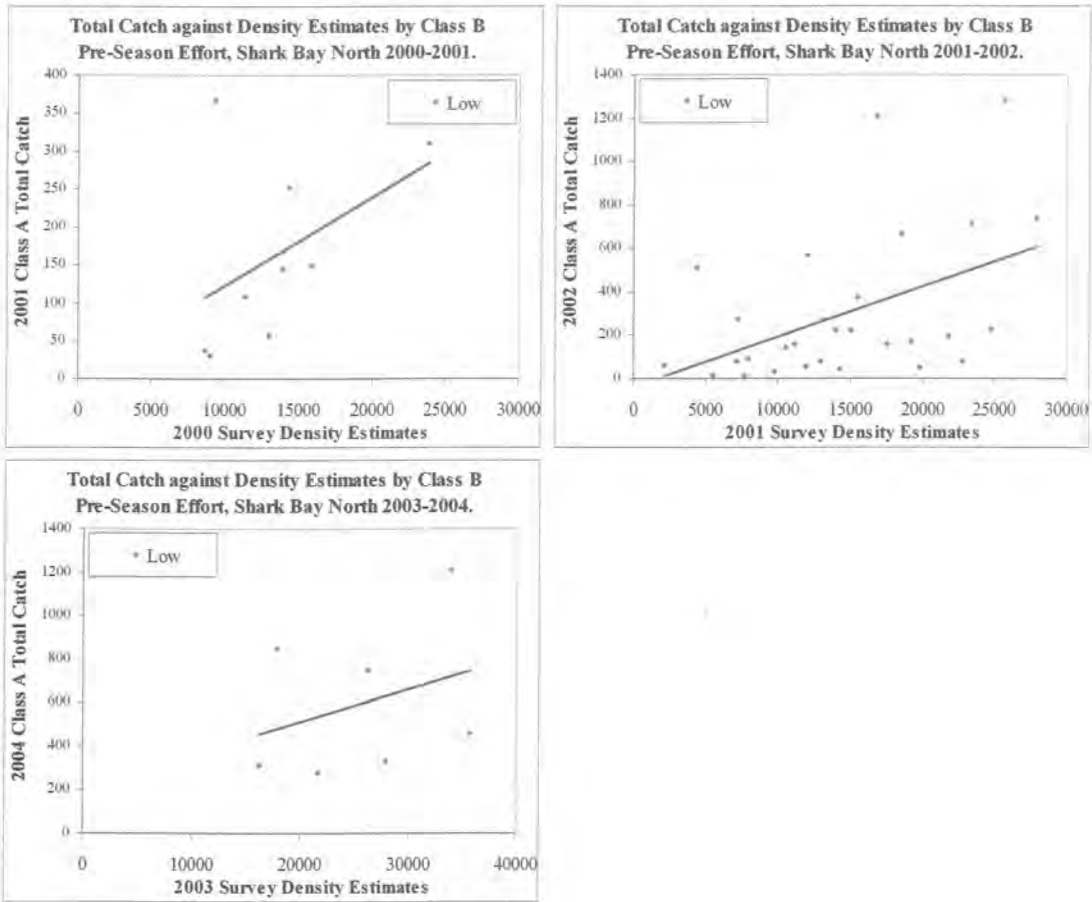

Figure 104: Scatter plots with fitted linear trend lines, Class A fleet total catch against density estimates by low Class B pre-season effort, Shark Bay North 2001, 2002 and 2004

Scatter plots of the scallop density estimates and the total catch of the Class A fleet at locations with no Class B pre-season effort (Figure 105) reveal that in each case there is a positive linear correlation between the variables. For each season this positive linear correlation is statistically significant at the 0.05 level.

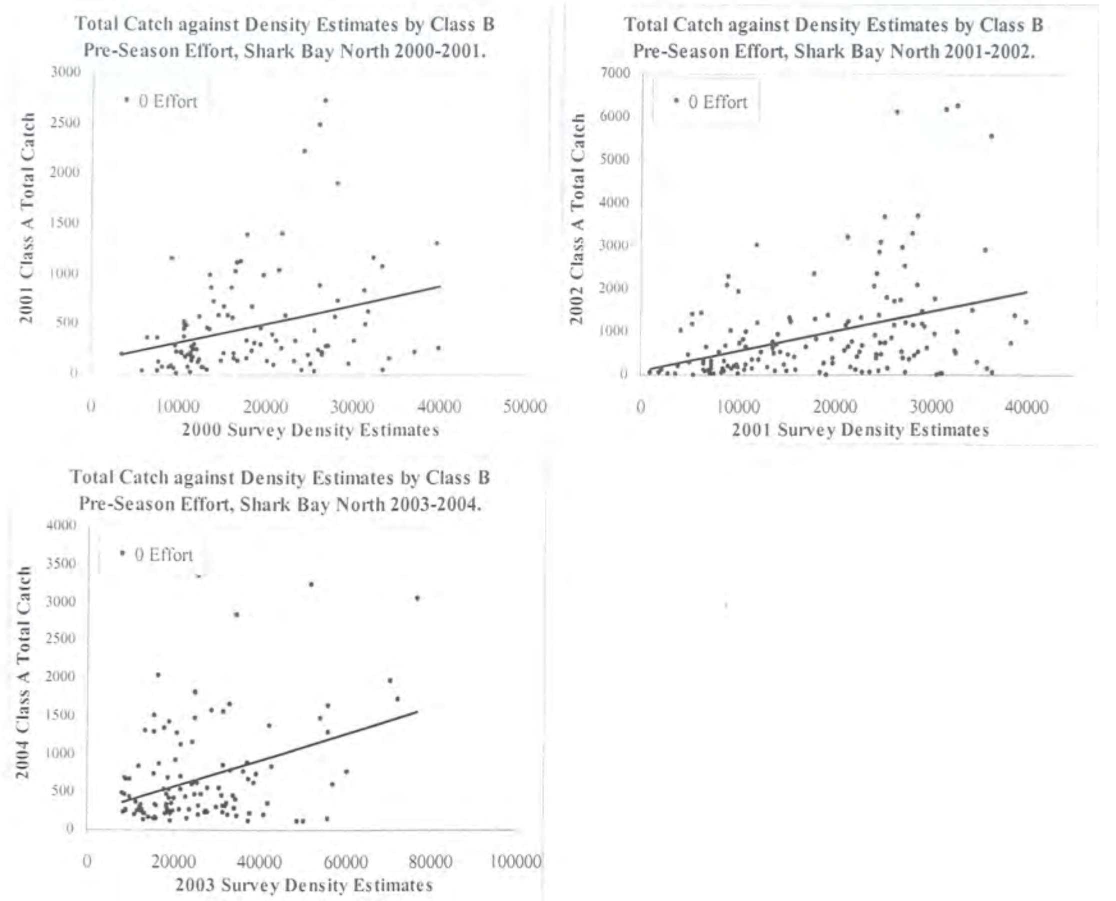

Figure 105: Scatter plots with fitted linear trend lines, Class A fleet total catch against density estimates by 0 Class B pre-season effort, Shark Bay North 2001, 2002 and 2004

The correlation coefficients of the relationship between the scallop density estimates and the total catch of the Class A fleet in Denham Sound are given by Class B pre-season effort in Table 27. Scatter plots of the corresponding data, with fitted trendlines, are displayed in Figure 106 to Figure 108.

Table 27: Pearson's correlation coefficients, Class A fleet total catch against density estimates by Class B fleet pre-season effort, Denham Sound
* indicates the value is significant at the 0.05 level

		Denham Sound			
Fishing Season	**> 0 Effort**	**High Effort**	**Medium Effort**	**Low Effort**	**No Effort**
2001	-0.159	n/a	n/a	n/a	-0.152
2002	-0.050	0.402	0.196	*-0.833	*-0.325
2003	0.636	n/a	n/a	n/a	*0.733

No noticeable patterns are present in the correlation coefficients for Denham Sound although there are several negative linear correlations given for this region whilst there are none for Shark Bay North. Subsequently, the relationship between the estimated scallop density and the total scallop catch of the Class A fleet does not appear to be effected by the pre-season fishing effort of the Class B fleet.

Scatter plots of the scallop density estimates against the total catch of the Class A fleet at locations with a class B pre-season effort value are displayed in Figure 106. These show that there is a weak negative linear correlation for the 2001 and 2002 seasons and a strong positive linear correlation for the 2003 season. In each case however the linear correlation is not statistically significant.

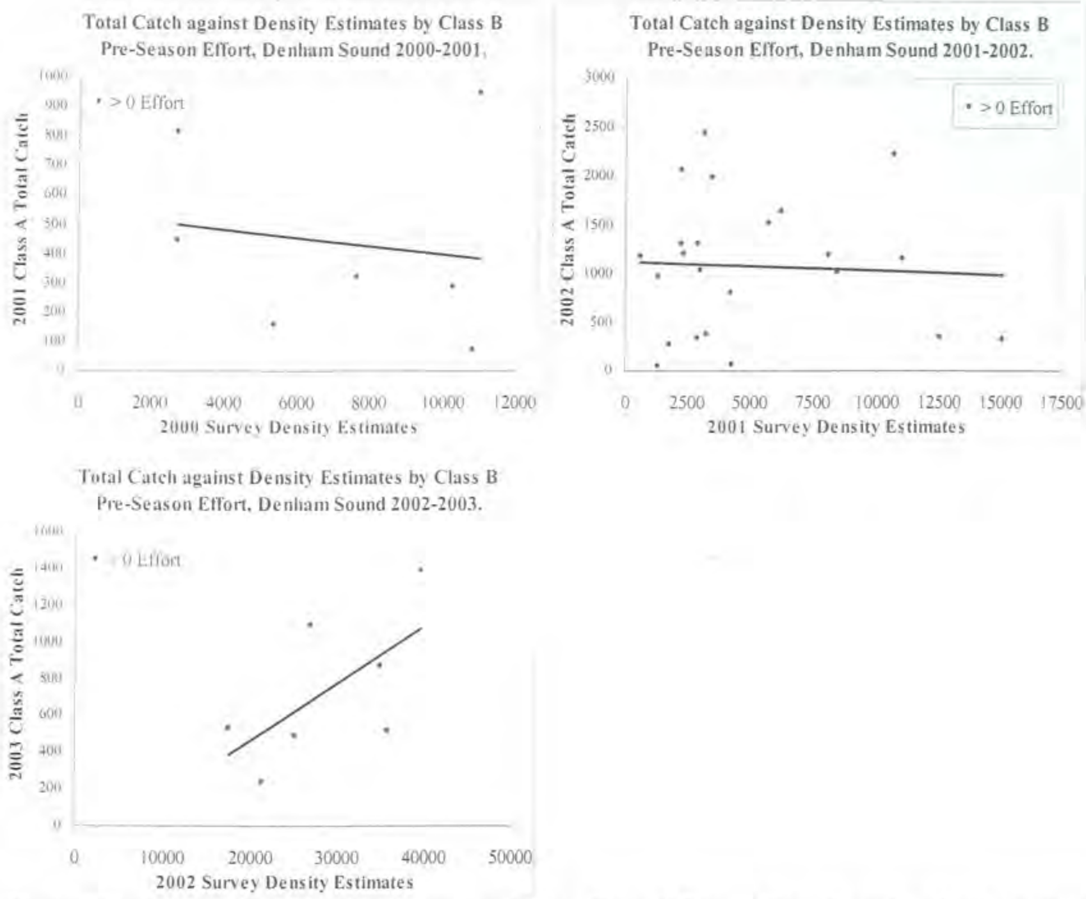

Figure 106: Scatter plots with fitted linear trend lines, Class A fleet total catch against density estimates by >0 Class B pre-season effort, Denham Sound 2001, 2002 and 2003

Only the 2002 fishing season contained enough pairs of co-located scallop density estimate and total catch of the Class A fleet data to allow useful scatter plots of these values to be constructed for locations with high, medium and low Class B pre-season effort. For the high and medium Class B pre-season effort categories there is a positive linear correlation that is not statistically significant while for the low Class B pre-season effort there is a statistically significant strong negative linear correlation between the estimated scallop density and the total catch of the Class A fleet.

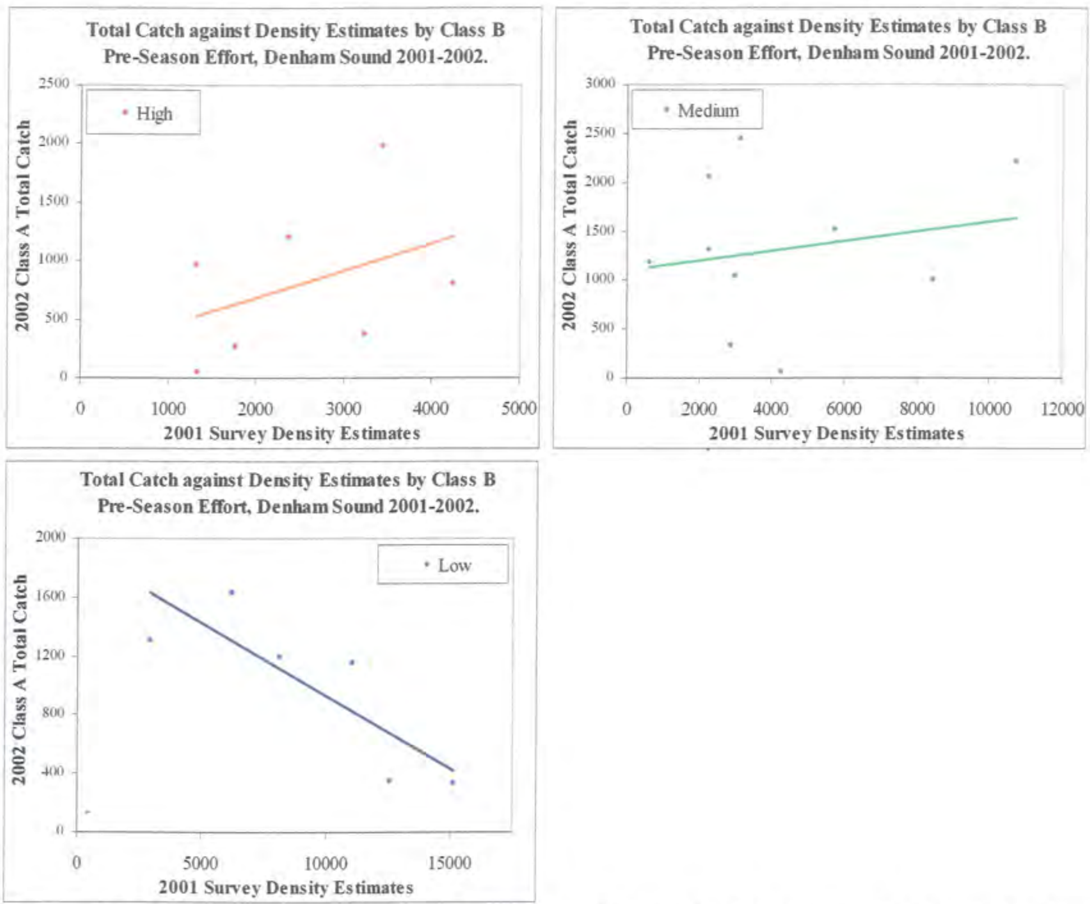

Figure 107: Scatter plots with fitted linear trend lines, Class A fleet total catch against density estimates by low, medium and high Class B pre-season effort, Denham Sound 2001

As displayed by the scatter plots in Figure 108, there are negative linear correlations between the scallop density estimates and the total catch of the Class A fleet at locations with no Class B pre-season effort for the 2001 and 2002 fishing seasons and a positive linear correlation between these variables for the 2003 season. This linear correlation however is only statistically significant for the 2002 and 2003 fishing seasons.

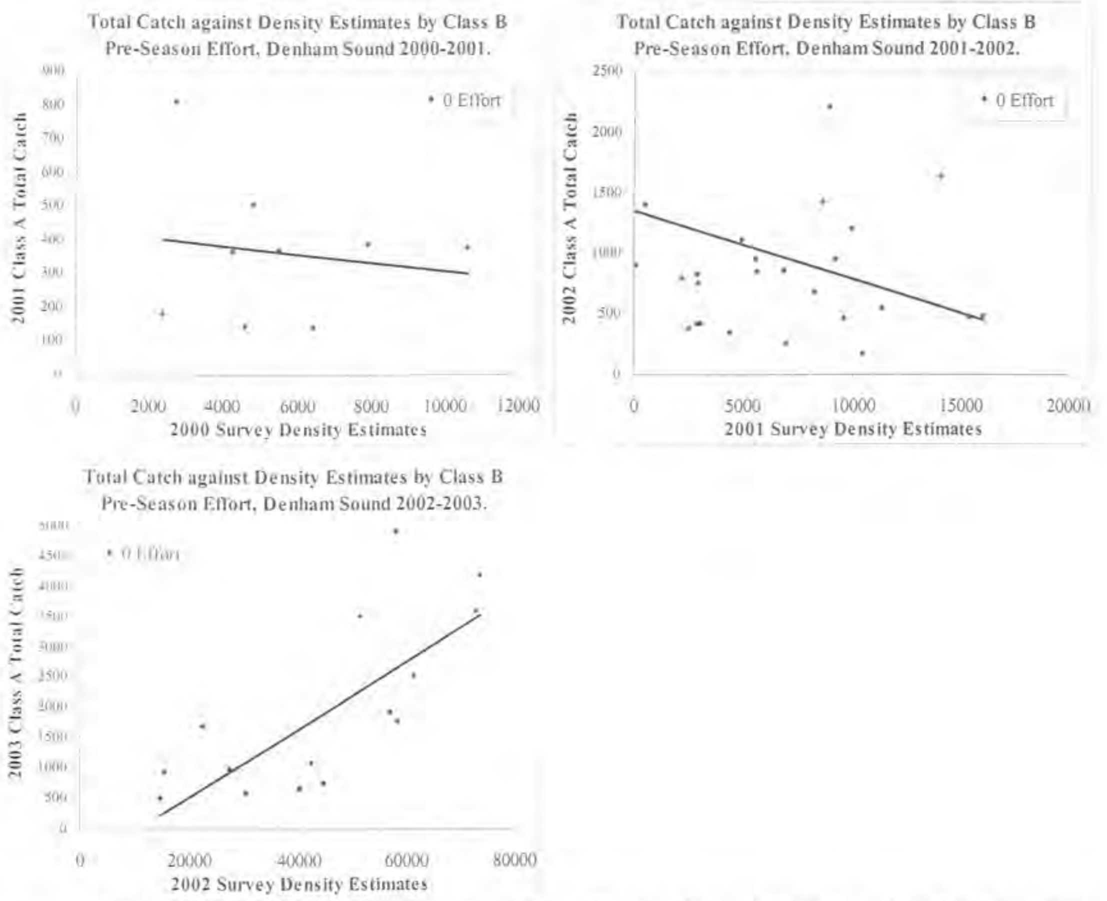

Figure 108: Scatter plots with fitted linear trend lines, Class A fleet total catch against density estimates by 0 Class B pre-season effort, Denham Sound 2001, 2002 and 2003

4.3. Spatial Rank Association

Measures of spatial rank association were calculated with a view to determining whether or not locations with a high level of Class B fleet fishing effort are spatially associated with locations that recorded a low scallop catch. Tjøstheim's Index of spatial association was used to measure this association between four different pairs of variables for each region and fishing season which contained a sufficient number of common locations. In this analysis, Tjøstheim's Indices with a value close to 1 indicate a strong spatial association between locations with high levels of Class B effort and low levels of scallop catch while values approaching -1 indicate disassociation between high Class B effort and low scallop catch.

4.3.1. Total Scallop Catch of the Class A Fleet and the Pre-Season Fishing Effort of the Class B Fleet

Spatial maps of the common locations for the total scallop catch of the Class A fleet and the pre-season fishing effort of the Class B fleet are displayed in Figure 109 to Figure 112. Only maps of the 2001, 2002 and 2004 fishing seasons for Shark Bay North and the 2002 season for Denham Sound are shown as the remaining seasons have an insufficient number of common locations for the calculation of a meaningful Tjøstheim's Index. These maps show that for Shark Bay North the common locations are spread across the Red Cliff and NW Peron fishing grounds and that there are no common location east of the Carnarvon-Peron line in the 2004 fishing season. The common locations for Denham Sound are positioned in the centre and northwest of the region.

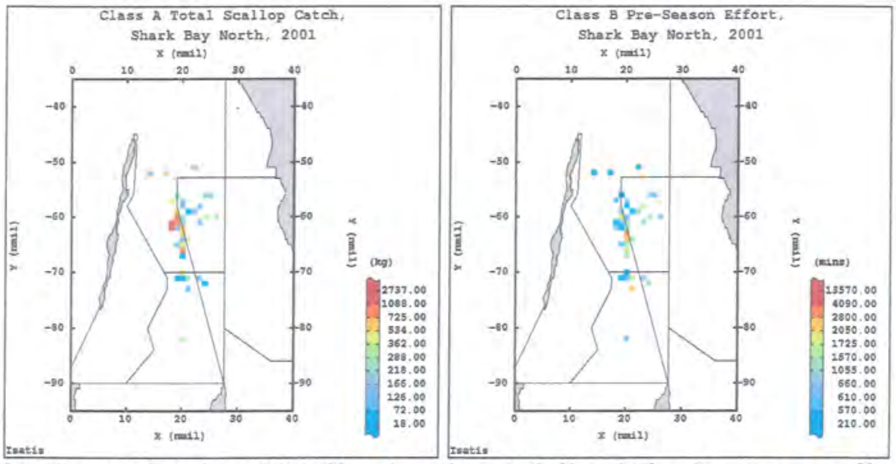

Figure 109: Common locations, 2001 Class A total catch (left) and Class B pre-season effort (right), Shark Bay North

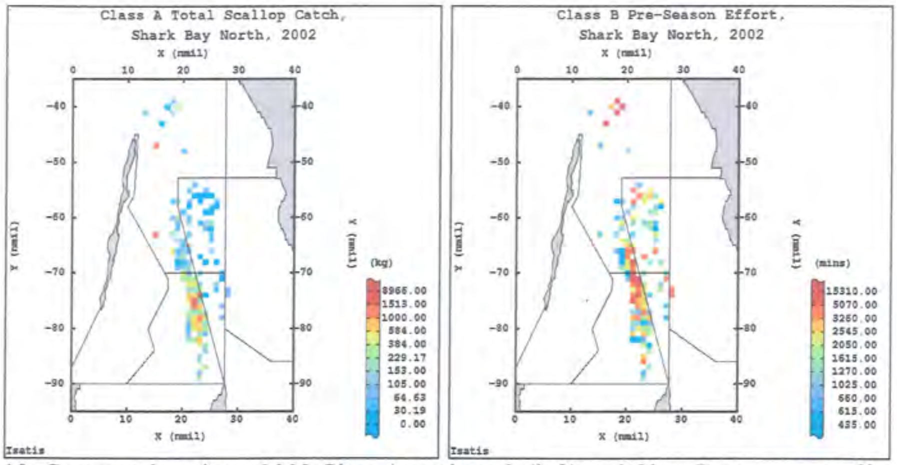

Figure 110: Common locations, 2002 Class A total catch (left) and Class B pre-season effort (right), Shark Bay North

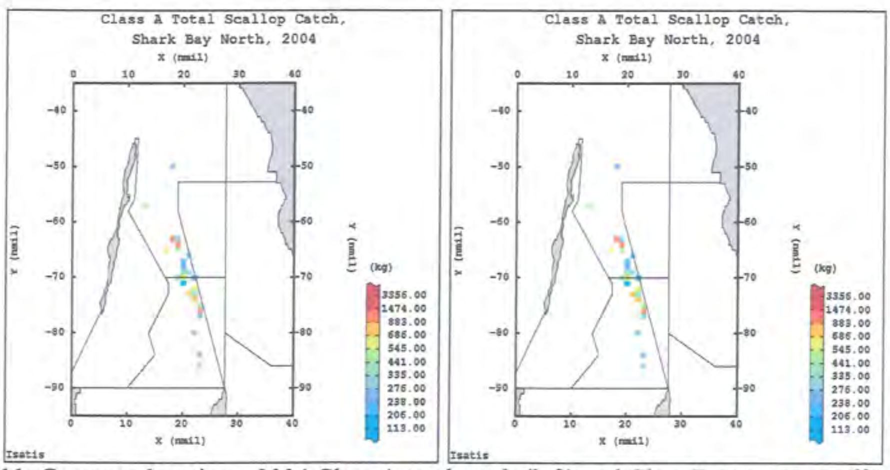

Figure 111: Common locations, 2004 Class A total catch (left) and Class B pre-season effort (right), Shark Bay North

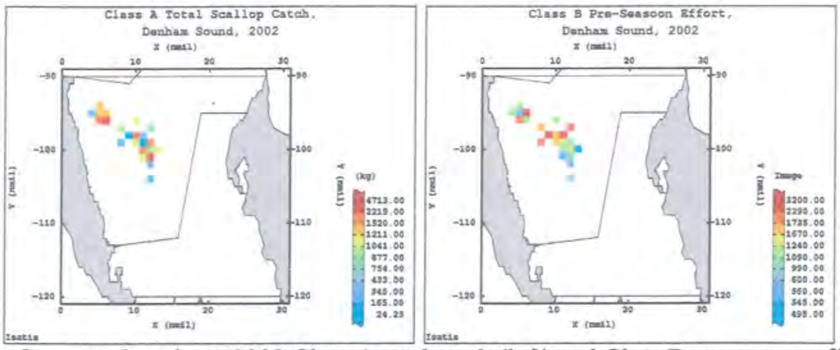

Figure 112: Common locations, 2002 Class A total catch (left) and Class B pre-season effort (right), Denham Sound

The Tjøstheim's Indices of spatial association between the total scallop catch of the Class A fleet and the pre-season fishing effort of the Class B fleet are displayed in Table 28 and Table 29 by fishing region. These show that in Shark Bay North there is a weak association between the variables for the 2001 and 2004 seasons and a weak disassociation for the 2002 season and that these are not statistically significant at the 0.05 level. Similarly in Denham Sound there is a weak disassociation for the 2002 and however it is not statistically significant.

Table 28: Tjøstheim's Index, Class A total catch and Class B pre-season effort, Shark Bay North

Shark Bay North				
Fishing Season	**N**	**Tjøstheim's Index**		
		A	**Quotient**	**Sig. at 0.05**
2000	3			
2001	39	0.151	1.324	No
2002	121	-0.066	-0.933	No
2003	0			
2004	26	0.010	0.000	No
2005	1			

Table 29: Tjøstheim's Index, Class A total catch and Class B pre-season effort, Denham Sound

Denham Sound				
Fishing Season	**N**	**Tjøstheim's Index**		
		A	**Quotient**	**Sig. at 0.05**
2000	0			
2001	7			
2002	23	-0.292	-1.518	No
2003	7			
2004	0			
2005	0			

4.3.2. Total Scallop Catch of the Class A Fleet and Total Fishing Effort of the Class B Fleet

Spatial maps of locations that contain values for both the total catch of the Class A fleet and the total fishing effort of the Class B fleet are displayed in Figure 113 to Figure 120. Maps of the Shark Bay North region for the 2000, 2003 and 2005 fishing seasons and of Denham Sound for the 2000 season have not been included as too few common locations are present in these data. These maps show that for Shark Bay North the common locations are found across much of the region and that in the 2002 season the co-located data in the west of Red Cliff typically have low values for the total fishing effort of the Class B fleet and high values for the total catch of the Class A fleet. For Denham Sound the common locations are found across much of the region with no striking patterns appearing between the level of fishing effort used by the Class B fleet and the size of the scallop catch achieved by the Class A fleet.

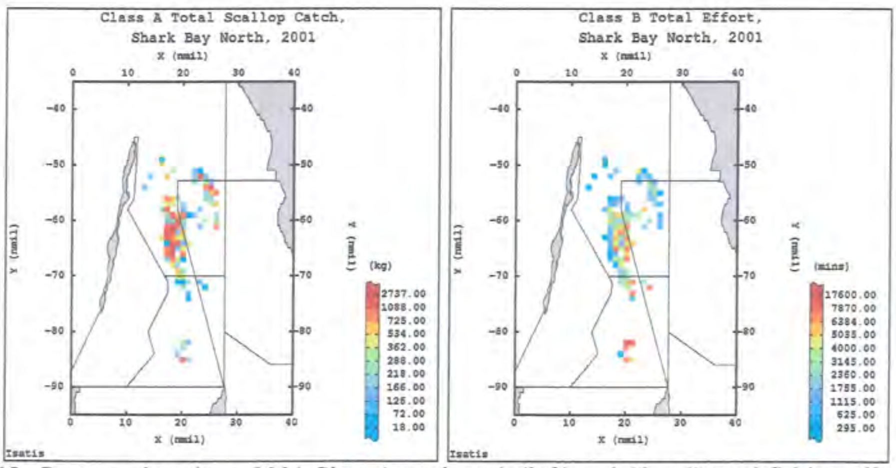

Figure 113: Common locations, 2001 Class A total catch (left) and Class B total fishing effort (right), Shark Bay North

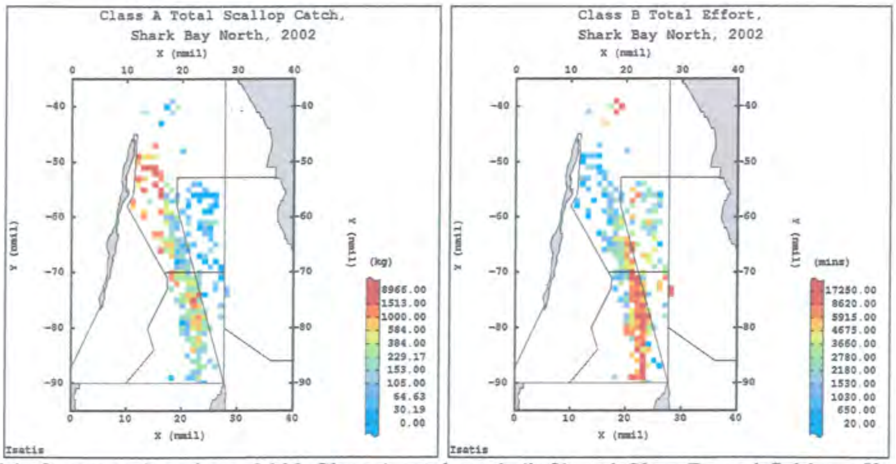

Figure 114: Common locations, 2002 Class A total catch (left) and Class B total fishing effort (right), Shark Bay North

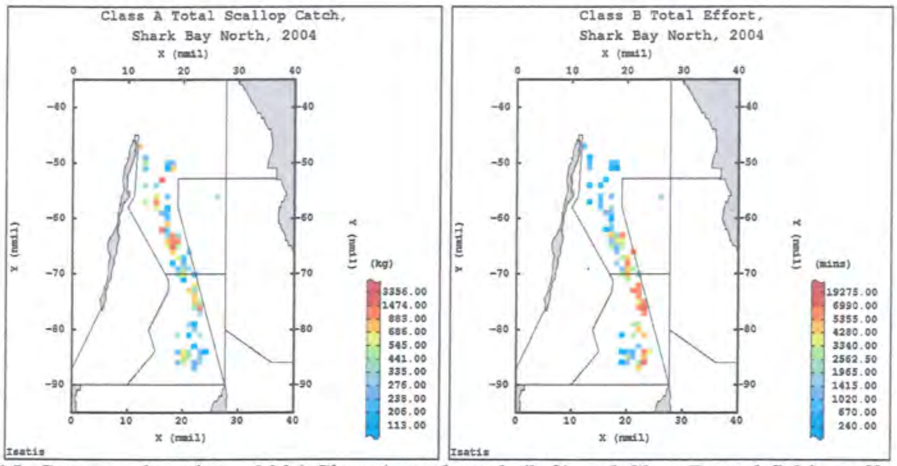

Figure 115: Common locations, 2004 Class A total catch (left) and Class B total fishing effort (right), Shark Bay North

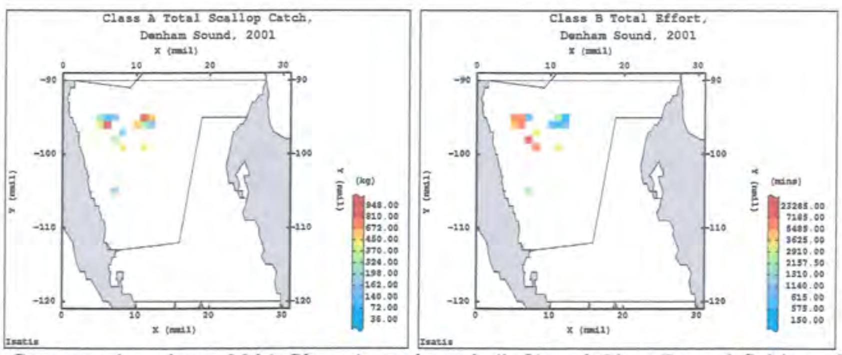

Figure 116: Common locations, 2001 Class A total catch (left) and Class B total fishing effort (right), Denham Sound

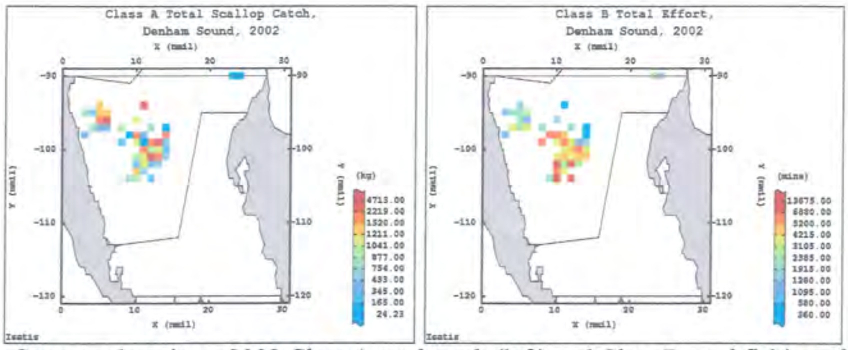

Figure 117: Common locations, 2002 Class A total catch (left) and Class B total fishing effort (right), Denham Sound

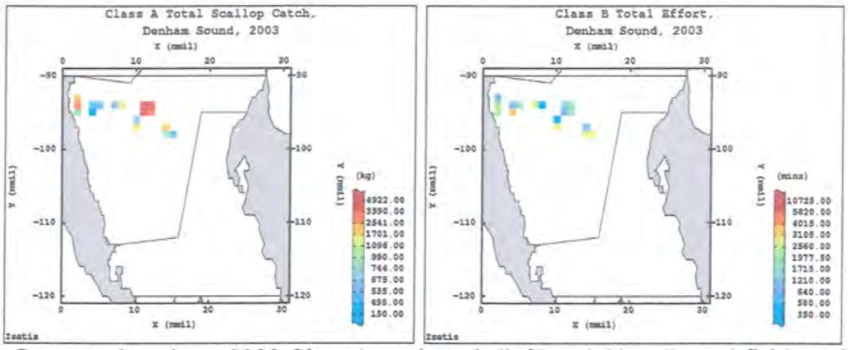

Figure 118: Common locations, 2003 Class A total catch (left) and Class B total fishing effort (right), Denham Sound

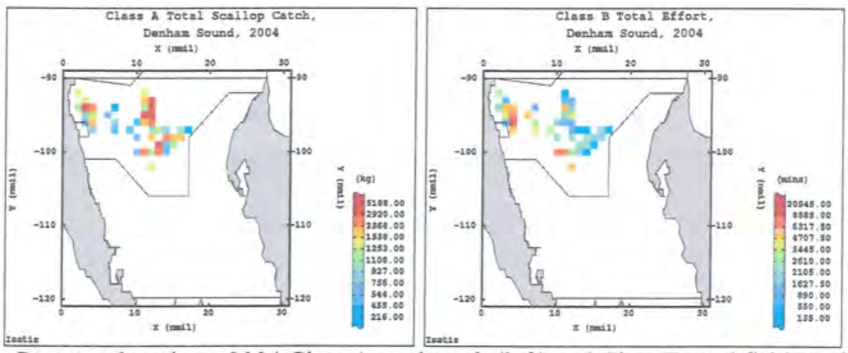

Figure 119: Common locations, 2004 Class A total catch (left) and Class B total fishing effort (right), Denham Sound

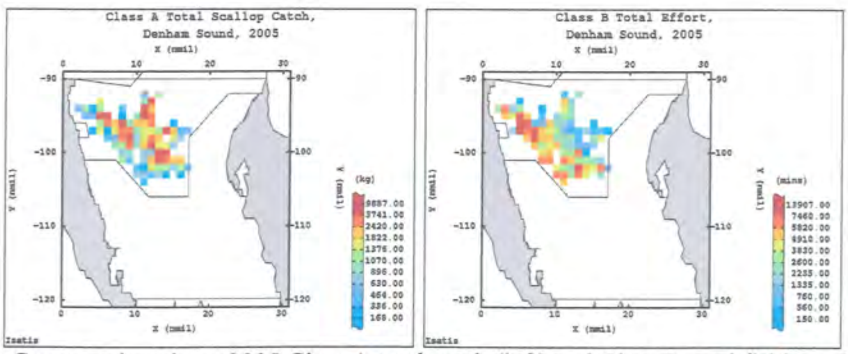

Figure 120: Common locations, 2005 Class A total catch (left) and Class B total fishing effort (right), Denham Sound

Tjøstheim's Indices of spatial association between the total scallop catch of the Class A fleet and the total fishing effort of the Class B fleet are displayed in Table 30 and Table 31. These reveal that for the 2001, 2002 and 2004 seasons in Shark Bay North there are weak associations between high effort and low catch however it is only statistically significant for the 2002 season. For Denham Sound there are statistically insignificant weak to very weak associations for the 2001 to 2005 fishing seasons.

Table 30: Tjøstheim's Index, Class A total catch and Class B total effort, Shark Bay North

Shark Bay North				
Fishing Season	**N**	**Tjøstheim's Index**		
		A	**Quotient**	**Sig. at 0.05**
2000	5			
2001	97	0.049	0.693	No
2002	207	0.167	3.049	Yes
2003	3			
2004	75	0.079	0.753	No
2005	10			

Table 31: Tjøstheim's Index, Class A total catch and Class B total effort, Denham Sound

Denham Sound				
Fishing Season	**N**	**Tjøstheim's Index**		
		A	**Quotient**	**Sig. at 0.05**
2000	0			
2001	15	0.194	1.022	No
2002	44	0.031	0.253	No
2003	17	0.225	1.049	No
2004	44	0.046	0.376	No
2005	91	0.002	0.024	No

4.3.3. Scallop Catch Rate of the Class A Fleet and Total Fishing Effort of the Class B Fleet.

Spatial maps of the common locations of the scallop catch rate of the Class A fleet and the total fishing effort of the Class B fleet are displayed in Figure 121 to Figure 128. Maps have not been included for seasons in which there were very few or no locations that contained both of these variables. No consistent spatial patterns between the values of the two variables are discernable however for Shark Bay North in 2002 the west of Red Cliff contains many locations that have a low fishing effort for the Class B fleet and a high scallop catch rate for the Class A fleet.

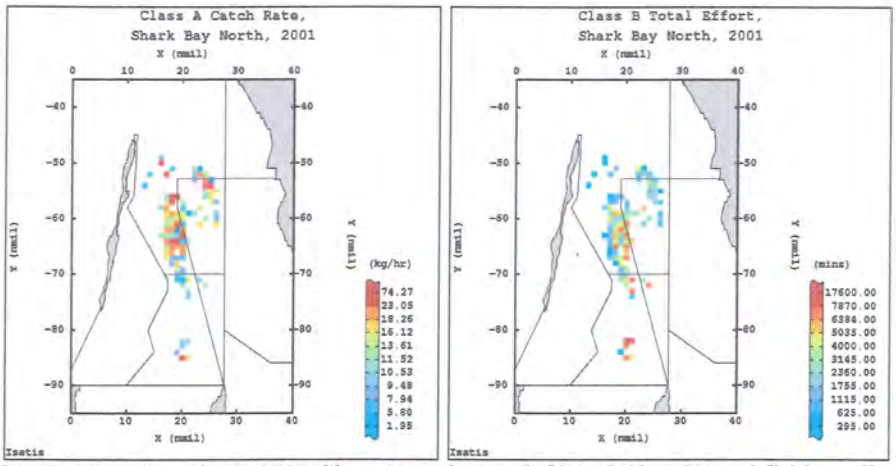

Figure 121: Common locations, 2001 Class A catch rate (left) and Class B total fishing effort (right), Shark Bay North

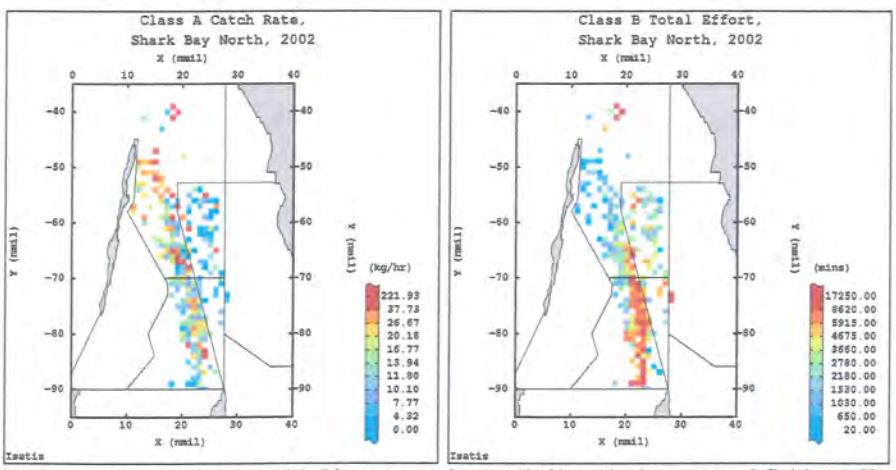

Figure 122: Common locations, 2002 Class A catch rate (left) and Class B total fishing effort (right), Shark Bay North

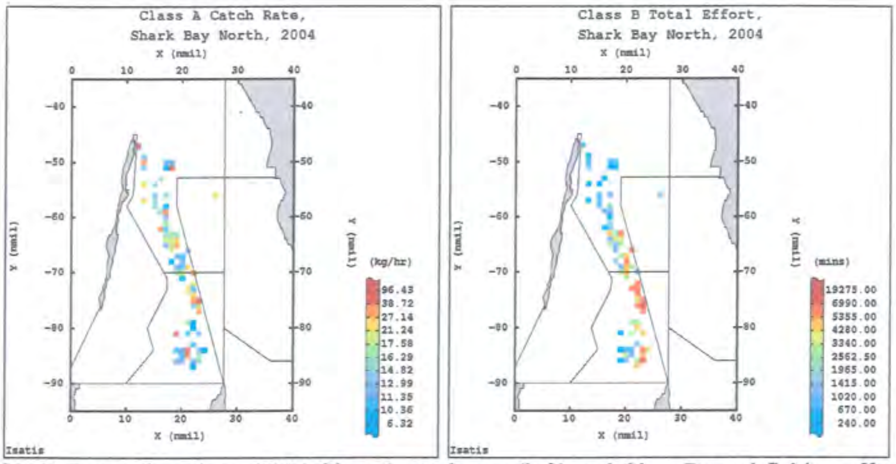

Figure 123: Common locations, 2004 Class A catch rate (left) and Class B total fishing effort (right), Shark Bay North

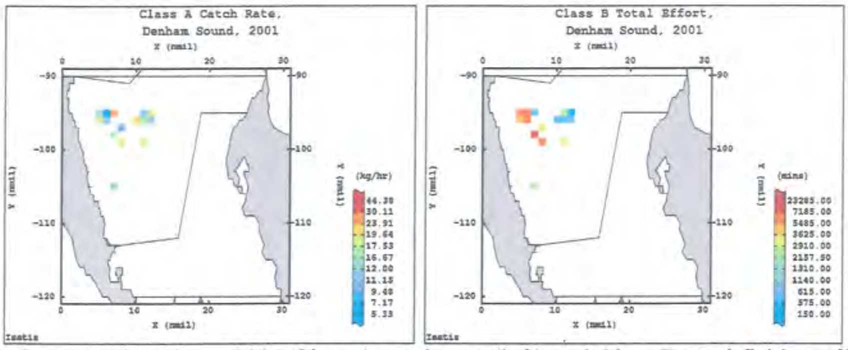

Figure 124: Common locations, 2001 Class A catch rate (left) and Class B total fishing effort (right), Denham Sound

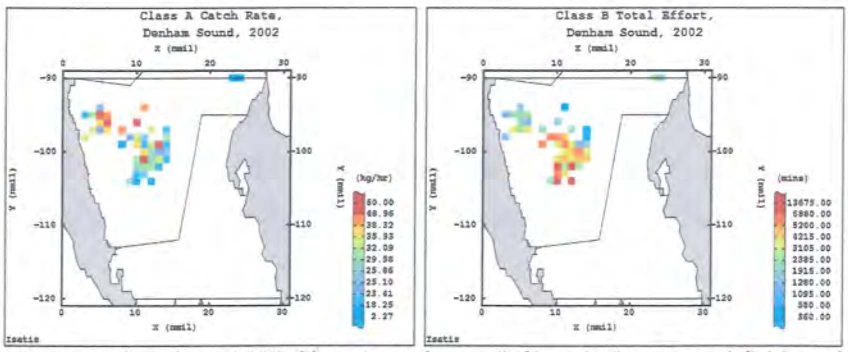

Figure 125: Common locations, 2002 Class A catch rate (left) and Class B total fishing effort (right), Denham Sound

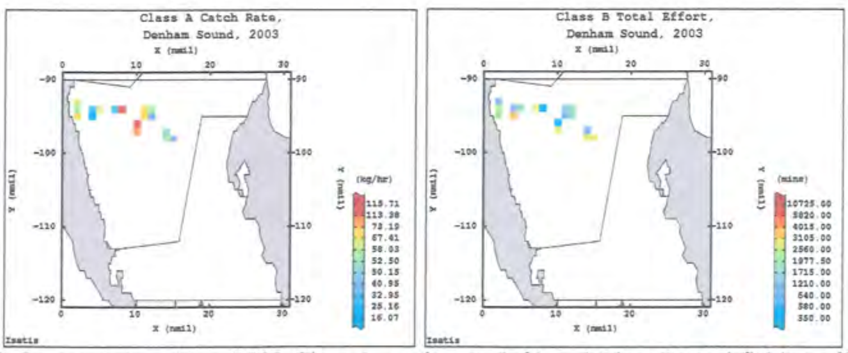

Figure 126: Common locations, 2003 Class A catch rate (left) and Class B total fishing effort (right), Denham Sound

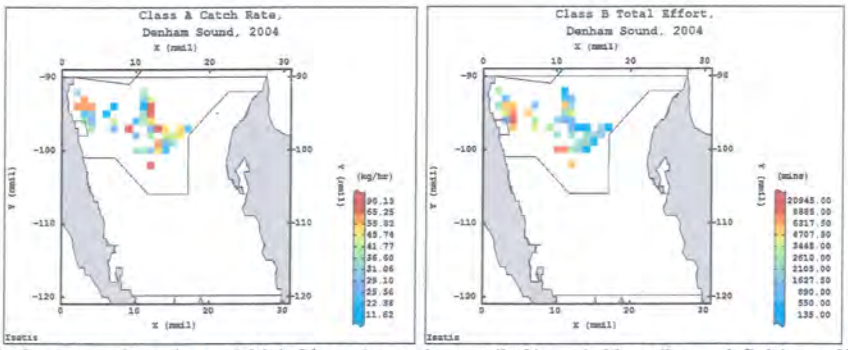

Figure 127: Common locations, 2004 Class A catch rate (left) and Class B total fishing effort (right), Denham Sound

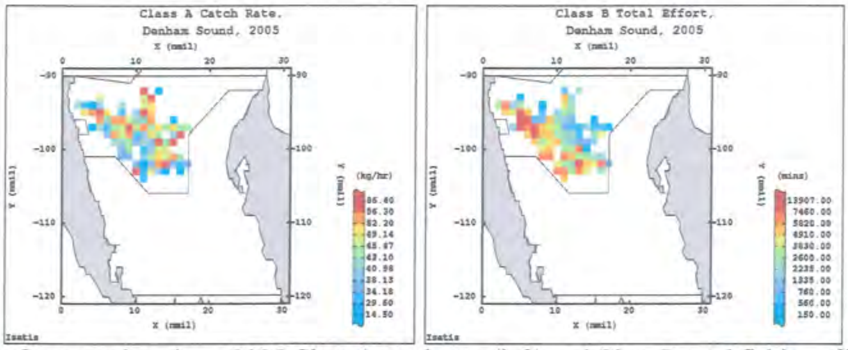

Figure 128: Common locations, 2005 Class A catch rate (left) and Class B total fishing effort (right), Denham Sound

Listed in Table 32 and Table 33 below are the Tjøstheim's Indices of the association between the catch rate of the Class A Fleet and the total effort of the Class B Fleet. For Shark Bay North these indicate that although there are statistically insignificant weak disassociations between low catch rates and high Class B effort for the 2001 and 2004 season there is a statistically significant weak association for the 2002 season. For the 2001 to 2005 fishing seasons in Denham Sound there are weak associations however they are only statistically significant for the 2001 and 2002 seasons.

Table 32: Tjøstheim's Index, Class A catch rate and Class B total effort, Shark Bay North

Shark Bay North				
Fishing Season	**N**	**Tjøstheim's Index A**	**Quotient**	**Sig. at 0.05**
2000	5			
2001	97	-0.060	-0.849	No
2002	207	0.115	2.100	Yes
2003	3			
2004	75	-0.091	-0.868	No
2005	10			

Table 33: Tjøstheim's Index, Class A catch rate and Class B total effort, Denham Sound

Denham Sound				
Fishing Season	N	Tjøstheim's Index		
		Â	Quotient	Sig. at 0.05
2000	0			
2001	15	0.382	2.013	Yes
2002	44	0.229	1.870	Yes
2003	17	0.100	0.466	No
2004	44	0.304	2.482	No
2005	91	0.047	0.562	No

4.3.4. Total Scallop Catch of the Combined Class A and B Fleet and Total Fishing Effort of the Class B Fleet

Locations that have values for both the total scallop catch, for both fleets combined, and the total fishing effort used by the Class B fleet are displayed in the spatial maps in Figure 129 to Figure 140 by region and fishing season. These show that for Shark Bay North there are many common locations in both the Red Cliff and NW Peron fishing grounds and that these locations are typically spread across much of the region. Similarly, for each season in Denham Sound these common locations are also numerous and they are located across most of the region.

Although there are no consistent spatial patterns between the size of the total scallop catch and the level of fishing effort applied by the Class B fleet, in some cases there are areas that contain many locations that have both high fishing effort and low scallop catch. For Denham Sound there are also no marked spatial patterns between the values of these two variables however in the 2002 and 2004 seasons there are many locations towards the south of region which have both a high level of fishing effort used by the Class B fleet and a low total scallop catch.

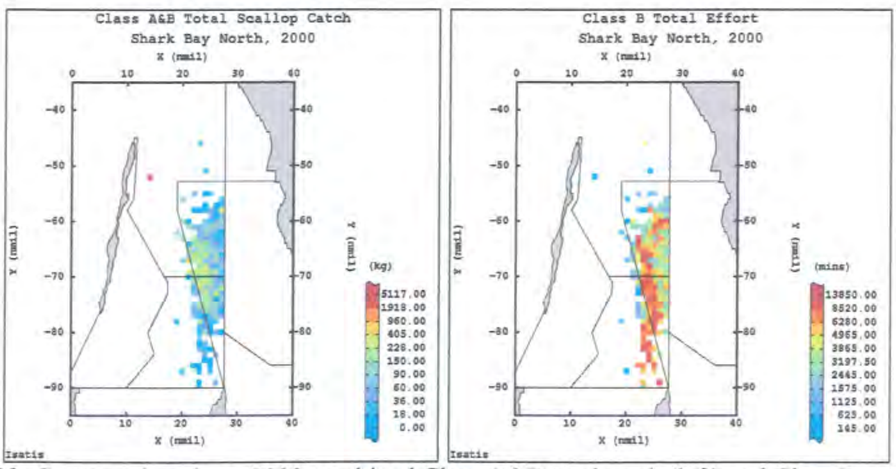

Figure 129: Common locations, 2000 combined Class A&B total catch (left) and Class B total fishing effort (right), Shark Bay North

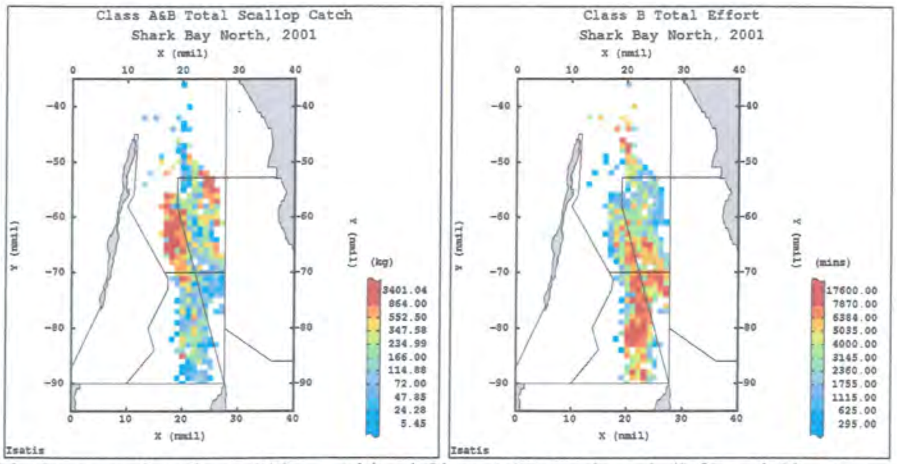

Figure 130: Common locations, 2001 combined Class A&B total catch (left) and Class B total fishing effort (right), Shark Bay North

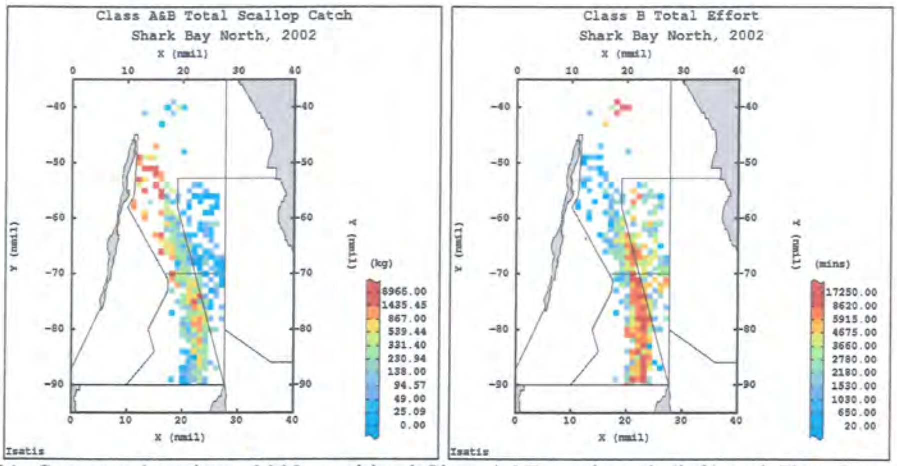

Figure 131: Common locations, 2002 combined Class A&B total catch (left) and Class B total fishing effort (right), Shark Bay North

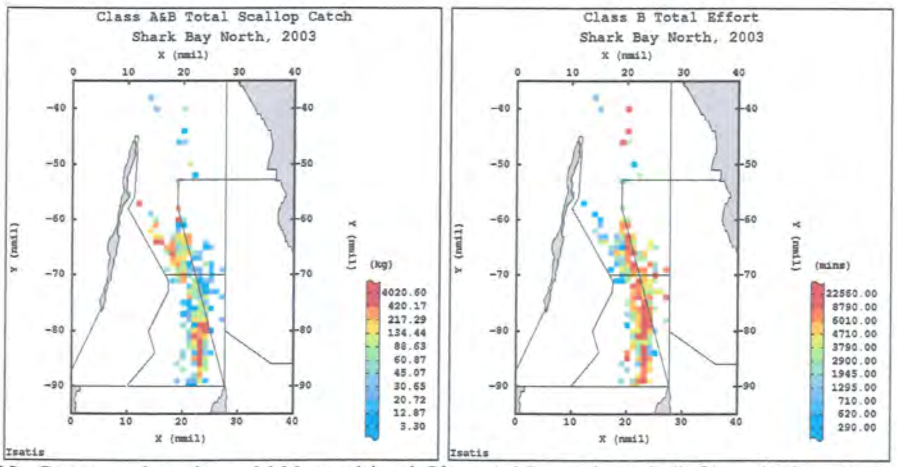

Figure 132: Common locations, 2003 combined Class A&B total catch (left) and Class B total fishing effort (right), Shark Bay North

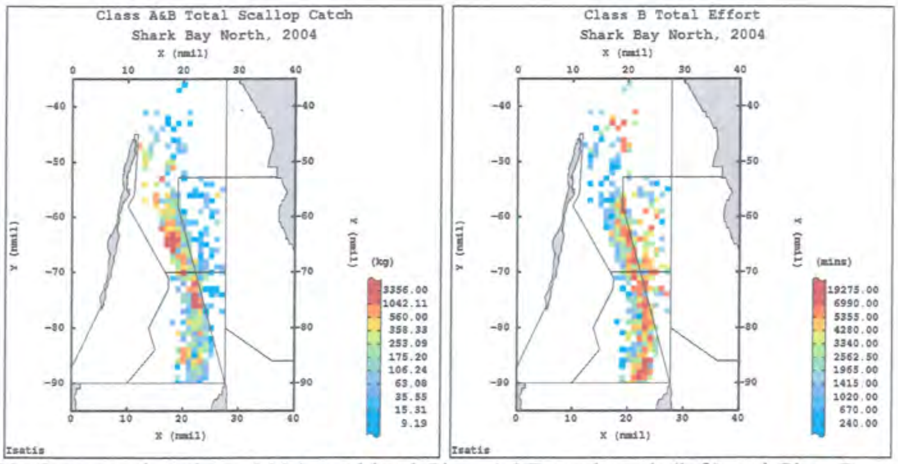

Figure 133: Common locations, 2004 combined Class A&B total catch (left) and Class B total fishing effort (right), Shark Bay North

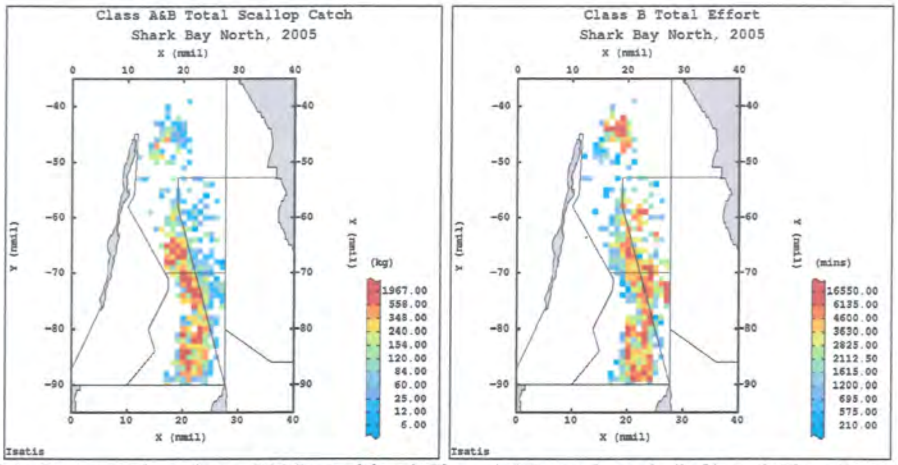

Figure 134: Common locations, 2005 combined Class A&B total catch (left) and Class B total fishing effort (right), Shark Bay North

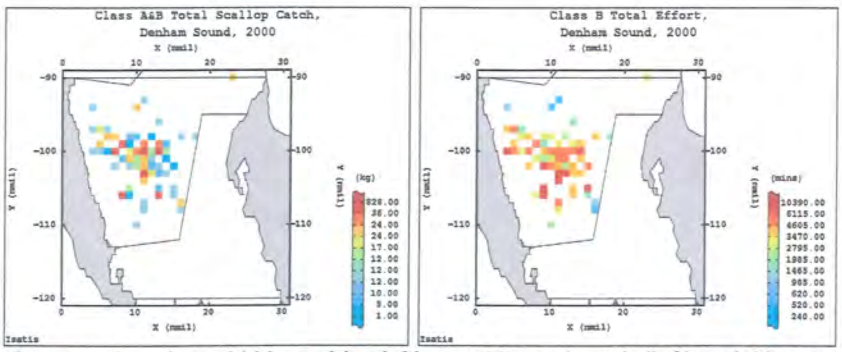

Figure 135: Common locations, 2000 combined Class A&B total catch (left) and Class B total fishing effort (right), Denham Sound

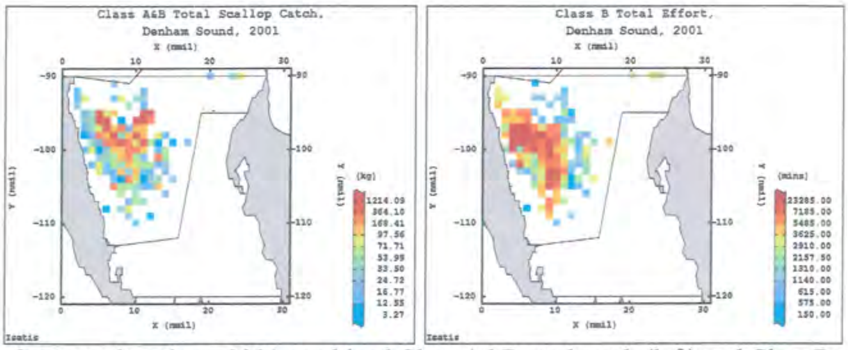

Figure 136: Common locations, 2001 combined Class A&B total catch (left) and Class B total fishing effort (right), Denham Sound

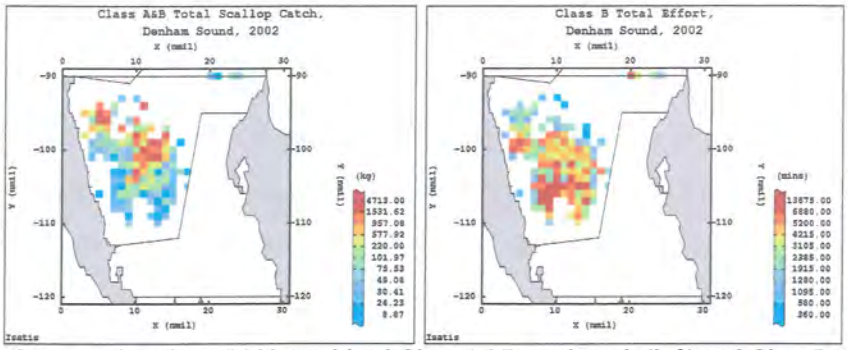

Figure 137: Common locations, 2002 combined Class A&B total catch (left) and Class B total fishing effort (right), Denham Sound

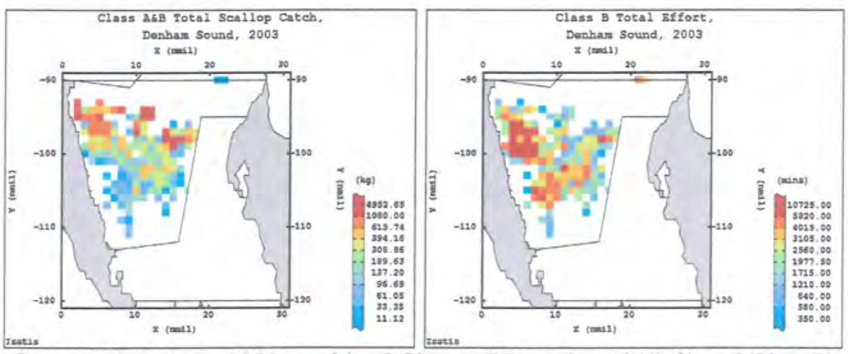

Figure 138: Common locations, 2003 combined Class A&B total catch (left) and Class B total fishing effort (right), Denham Sound

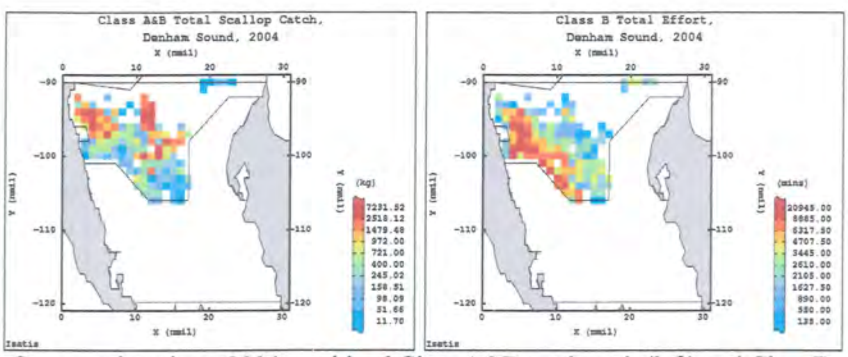

Figure 139: Common locations, 2004 combined Class A&B total catch (left) and Class B total fishing effort (right), Denham Sound

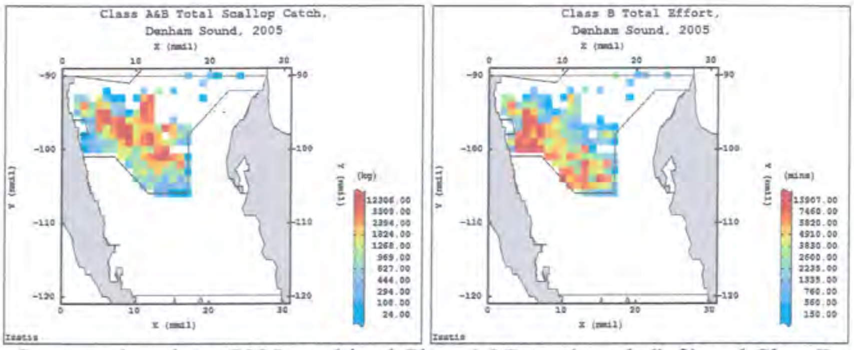

Figure 140: Common locations, 2005 combined Class A&B total catch (left) and Class B total fishing effort (right), Denham Sound

The Tjøstheim's Indices calculated for the association between the Class A and B fleet scallop catch and Class B fleet fishing effort. The resulting values are displayed in Table 34 and Table 35 below. These show that for each season in Shark Bay North there is a weak association between low total catch and high Class B fishing effort however it is only statistically significant for the 2000, 2001 and 2004 seasons. In Denham Sound there is statistically significant weak association for the 2002 and 2004 fishing seasons with statistically insignificant weak associations/disassociations for the remaining seasons.

Table 34: Tjøstheim's Index, Class A and B total catch and Class B total effort, Shark Bay North

Shark Bay North				
Fishing Season	**N**	**Tjøstheim's Index**		
		A	**Quotient**	**Sig. at 0.05**
2000	166	0.152	2.762	Yes
2001	323	0.106	2.601	Yes
2002	257	0.045	0.910	No
2003	158	0.055	0.865	No
2004	262	0.094	1.910	Yes
2005	297	0.007	0.165	No

Table 35: Tjøstheim's Index, Class A and B total catch and Class B total effort, Denham Sound

Denham Sound				
Fishing Season	**N**	**Tjøstheim's Index**		
		A	**Quotient**	**Sig. at 0.05**
2000	61	-0.091	-0.875	No
2001	131	0.048	0.723	No
2002	131	0.149	2.251	Yes
2003	153	0.033	0.559	No
2004	133	0.126	1.848	Yes
2005	148	-0.022	-0.347	No

4.4. Interaction between Class B Fishing Effort and the Subsequent Recruitment Density

To further explore the interaction between the Class A and Class B fleets in Shark Bay the relationship between the level of fishing effort applied by Class B fleet and the number of recruit scallops present later in the year was analysed. In order to achieve this, the total fishing effort spent by the Class B fleet during the main spawning period, May to July, for each season under consideration was compared to the density of recruit scallops, as estimated from the following scallop survey. These comparisons were made at 36 locations within a specific area of interest defined by the WA Department of Fisheries. This study area, located in the Shark Bay North region between latitudes 25° 6.0' and 25° 19.4', is displayed in Figure 141.

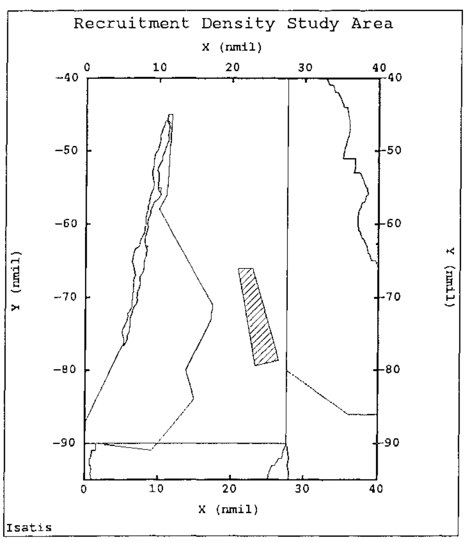

Figure 141: Recruitment Density Study Area (shaded)

4.4.1. Spatial Maps of the Study Area

Spatial maps of the total fishing effort used by the Class B fleet within the study area during the spawning period are displayed in Figure 142 and Figure 143 together with the subsequent recruit scallop density. The locations displayed in these maps do not exhibit a marked relationship between the level of fishing effort used during the spawning period and the density of recruit scallops. Typically, areas of high fishing effort do not correspond with areas of low recruit density and areas of low effort do not correspond to areas of high recruit density. For the 2000, 2002 and 2005 seasons areas of low recruit density were located in areas of low fishing effort.

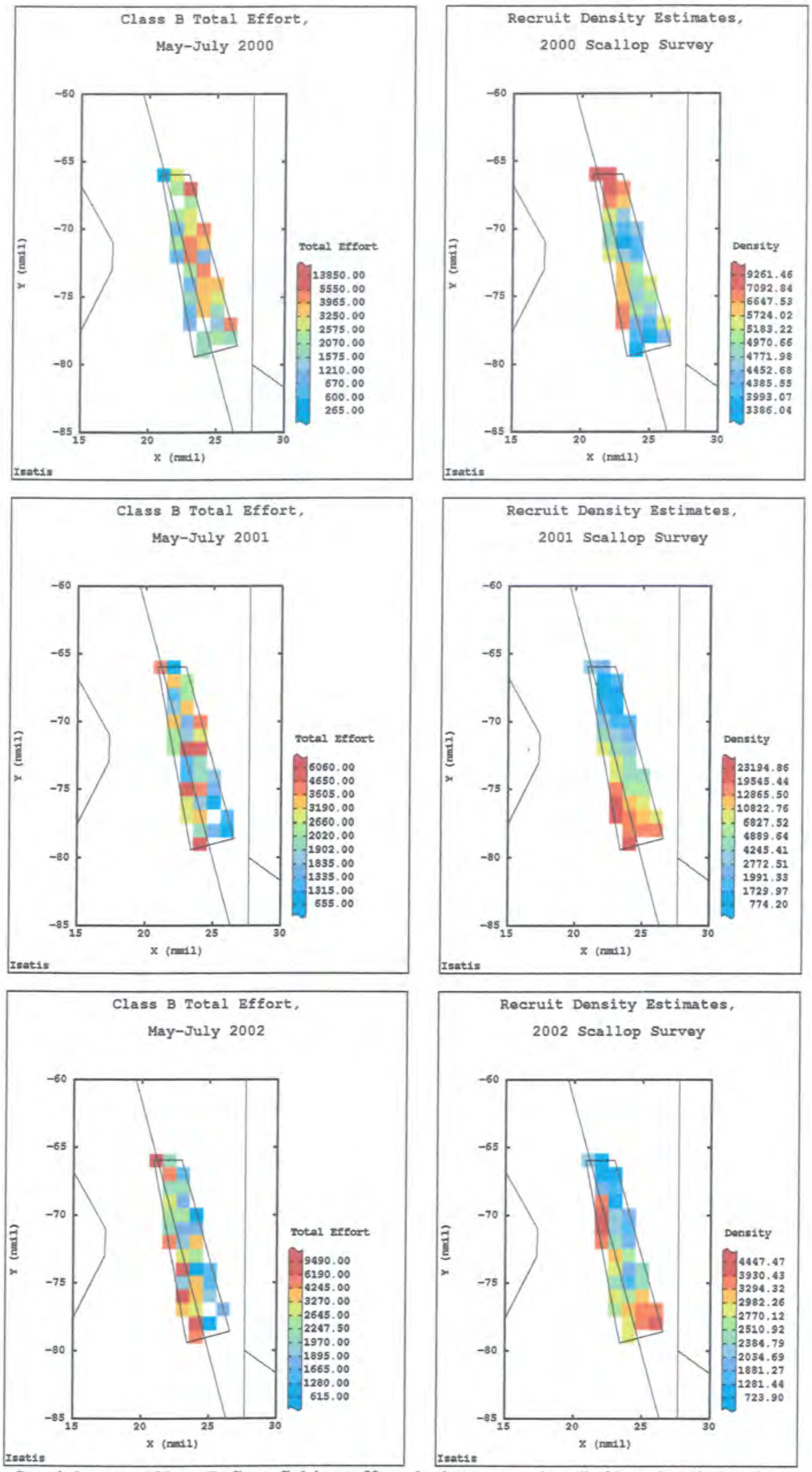

Figure 142: Spatial maps, Class B fleet fishing effort during spawning (left) and estimated recruit density (right), Study Area 2000 - 2002

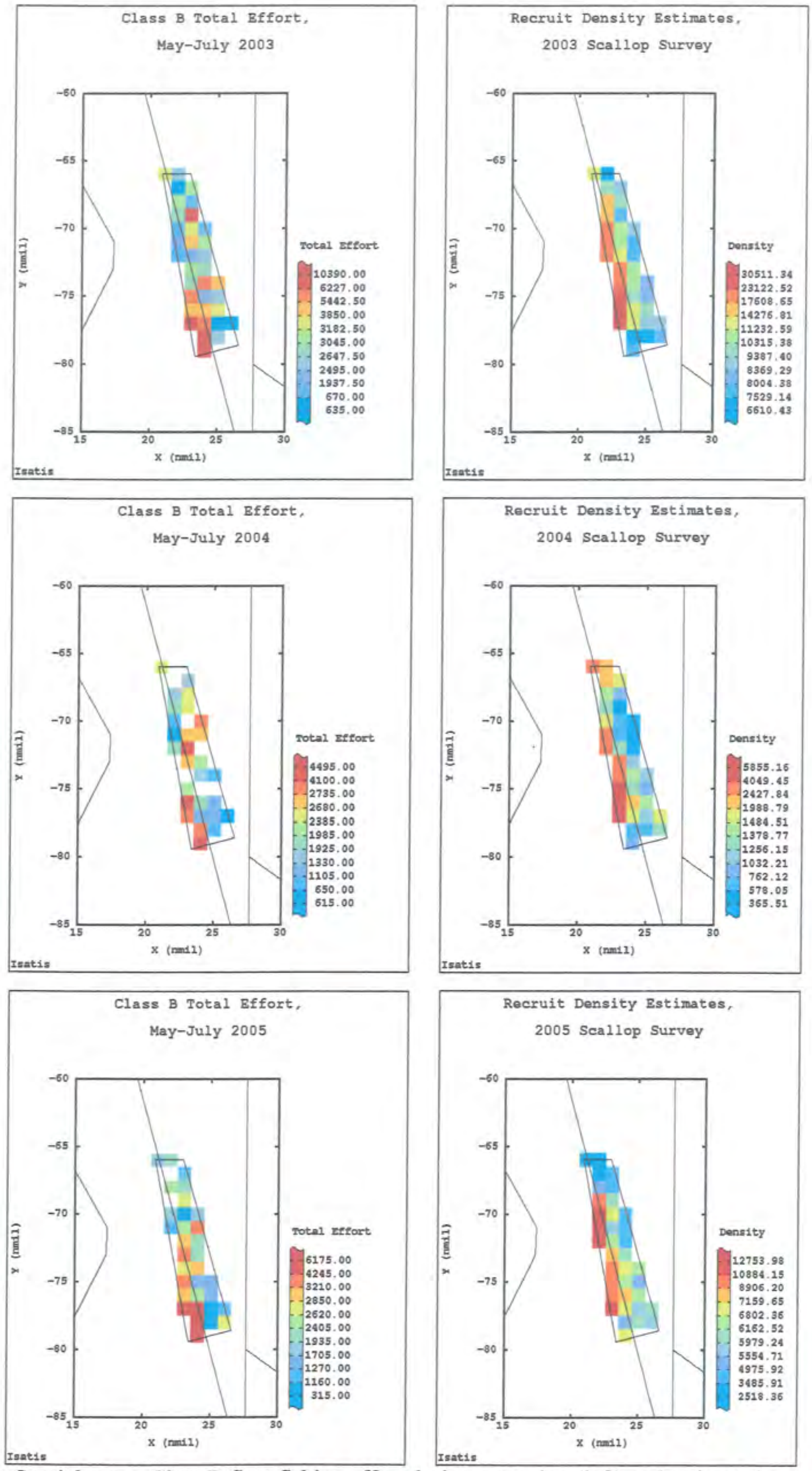

Figure 143: Spatial maps, Class B fleet fishing effort during spawning (left) and estimated recruit density (right), Study Area 2003 - 2005

4.4.2. Correlation between the Fishing Effort of the Class B Fleet and Estimated Recruit Scallop Density

Scatter plots of the estimated recruit density, at locations within the study area, against the fishing effort used by the Class B fleet during the spawning period at those locations are displayed in Figure 144. No strong patterns are noticeable in these plots although a weak declining linear trend in the recruit density is displayed for the 2000 season while weak increasing linear trends are present in the 2003 to 2005 seasons.

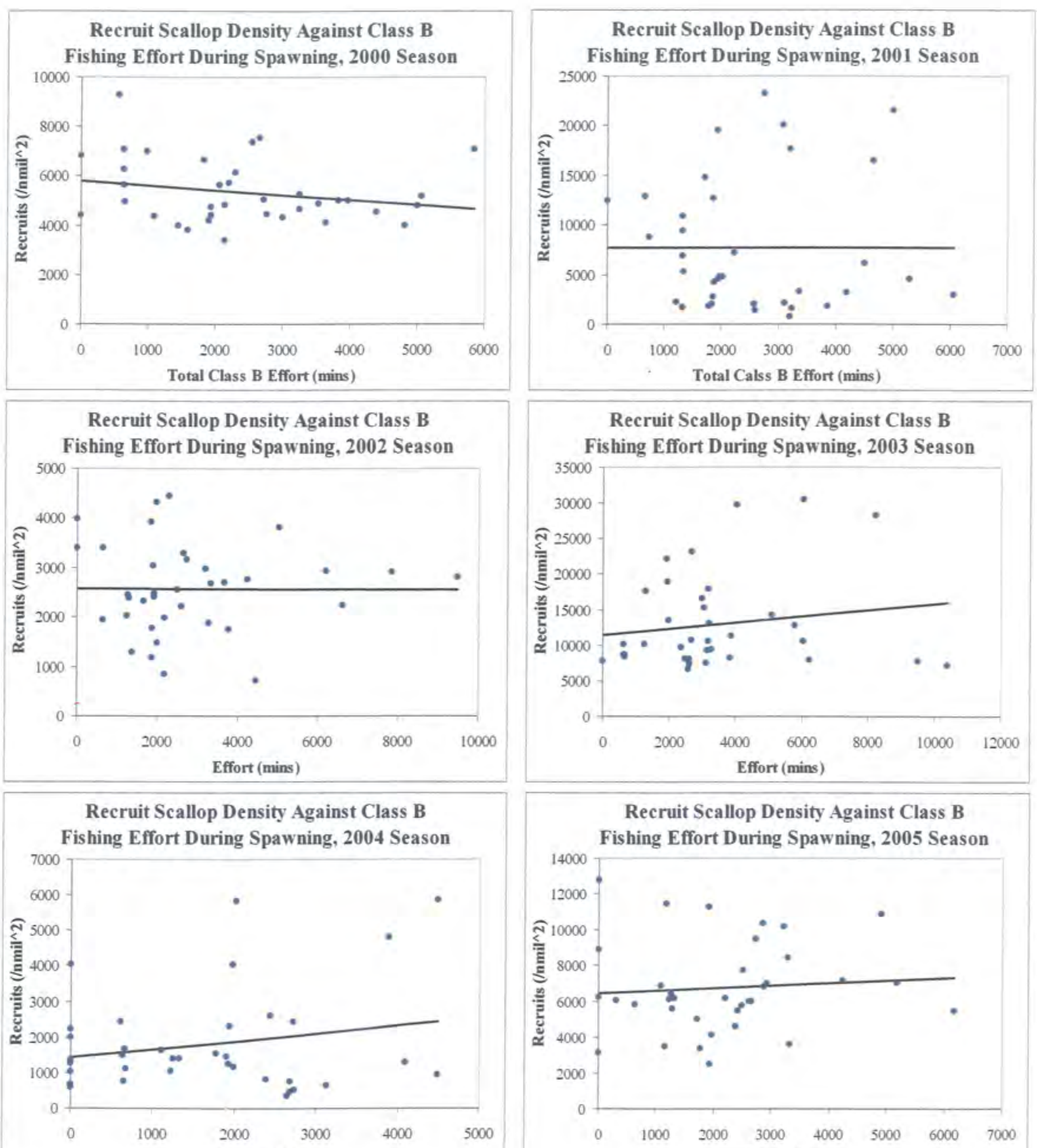

Figure 144: Scatter plots, estimated recruit scallop density against the total fishing effort of the Class B fleet during the spawning period

The corresponding Pearson's and Spearman's correlation coefficients between the two variables for each season under consideration are listed in Table 36. These show that there are no statistically significant linear correlations, at the 0.05 significance level, between the total fishing effort used by the Class B fleet during the spawning period and the recruit scallop density within the study area. For each season the correlation between the two variables was weak to very weak.

Table 36: Correlation coefficients, estimated recruit scallop density against the total fishing effort of the Class B fleet during the spawning period

		Pearson's		**Spearman's**	
Season	**N**	**r**	**Sig. at 0.05**	**rho**	**Sig. at 0.05**
2000	36	-0.227	No	-0.169	No
2001	36	0.002	No	-0.110	No
2002	36	-0.008	No	0.010	No
2003	36	0.158	No	0.116	No
2004	36	0.212	No	-0.026	No
2005	36	0.077	No	0.145	No

4.4.3. Spatial Rank Association of Class B Fishing Effort and Recruit Scallop Density

In order to measure the spatial association between locations with a high fishing effort recorded by the Class B fleet during the spawning period and locations with a low recruit scallop density, and vice versa, Tjøstheim's indices were calculated using values located within the study area. These indices were calculated by ranking the fishing effort values in ascending order and the recruit density values in descending order so as a index of 1 indicates strong spatial association between locations with high effort and locations with low recruit density while an index of -1 indicates strong disassociation.

The resulting Tjøstheim's indices and the corresponding test statistics for each fishing season are displayed in Table 37. These show that for the 2004 season there is a statistically significant, at the 0.05 significance level, moderate disassociation between high Class B fishing effort during the spawning season and low recruit density. The Tjøstheim's indices for the 2000 and 2003 seasons indicate weak association between high effort and low recruit density, however, they are not statistically significant. No association is present within the study area for the remaining seasons as indicated by indices of approximately 0.

Table 37: Tjøstheim's indices, estimated recruit scallop density against the total fishing effort of the Class B fleet during the spawning period

		Tjøstheim's Index		
Season	**N**	**A**	**Quotient**	**Sig. at 0.05**
2000	36	0.248	1.675	No
2001	36	0.083	0.560	No
2002	36	-0.030	-0.203	No
2003	36	0.115	0.779	No
2004	36	-0.349	-2.360	Yes
2005	36	-0.009	-0.064	No

5. Conclusion and Discussion

5.1. Conclusions

This thesis set out to gain an understanding of the extent of interaction between the Class A and Class B fleets in Western Australia's Shark Bay Scallop Managed Fishery during the 2000 to 2005 fishing seasons. In particular, it aimed to identify and measure the relationship that the level of fishing effort used by the Class B fleet has with the size of the subsequent scallop catch of the Class A fleet. This was achieved by investigating associations between the total fishing effort used by the Class B fleet, over both the entire season and before the start of scallop fishing, and the total amount of scallops caught, by both fleets combined and the Class A fleet individually. The results obtained from a study into the relationship between the fishing effort used by the Class B fleet during the main spawning period and the density of recruit scallops recorded by the following survey have also been presented. To allow for comparisons to be made between data sets the variables of interest were aggregated, using moving window statistics, onto a 1x1 nautical mile regular grid.

Initially, spatial maps of several variables were examined for the presence of spatial patterns. This included comparing the spatial maps of the estimated total scallop density, calculated using lognormal kriging of the relevant survey data, with spatial maps of both the total scallop catch and catch rate recorded for the following season. This indicated that for the Shark Bay North region the spatial patterns of the density estimates are comparable to those for the total catch and even more similar to the spatial patterns of the catch rate, especially in the NW Peron fishing ground. For Denham Sound, the spatial patterns of the 2002 to 2004 density estimates are representative of the spatial patterns present in both the total catch and catch rate values for the subsequent fishing seasons.

For each season under consideration, spatial maps of the pre-season fishing effort used by the Class B fleet and the total scallop catch recorded by the Class A fleet were also examined. This revealed that in the Shark Bay North region locations fished by the Class A fleet were not typically fished by the Class B fleet before the start of the scallop season with the areas of greatest overlap located in NW Peron and along the east of Red Cliff fishing grounds. In addition to this, no marked patterns were observed between the amount of pre-season fishing effort used by the Class B fishing fleet and the size of the total scallop catch recorded by the Class A fleet in both the Shark Bay North and Denham Sound regions.

Spatial maps of the total fishing effort applied by the Class B fleet were also compared with the total scallop catch for both fleets combined. The maps of the Shark Bay North region showed that although no distinct spatial patterns are noticeable between these two variables some areas of high Class B fishing effort in the Red Cliff fishing ground often contain several locations of low scallop catch. These areas however typically also have a low estimated scallop density. Similarly, no marked spatial patterns were displayed in the spatial maps of these two variables for Denham Sound.

Scatter plots and correlation coefficients were also computed for variables of interest to investigate any trends that were present in the data. These showed that for the Shark Bay North region there was typically statically significant positive linear correlation between the total scallop density estimates and the total scallop catch of the two fleets combined with locations of high estimated scallop density generally corresponding with locations of high scallop catch. In Denham Sound there was generally a weak to moderate positive linear correlation between these two variables and for the 2003 to 2005 fishing seasons this correlation was statistically significant. These results provide further evidence that the total scallop density, as estimated from the scallop survey results, is indicative of the total scallop catch achieved in the following fishing season.

The correlation between the scallop density estimates and the total catch was also analysed separately for locations with high, medium and low levels of total fishing effort recorded by the Class B fleet as well as for locations that were not fished by the Class B fleet. The subsequent scatter plots and correlation coefficients did not reveal any marked patterns between the strength of the linear correlation of these variables and the level of total fishing effort used by the Class B fleet. This indicates that the relationship between the scallop density estimates and the total catch of the Class A fleet is not affected by the overall fishing effort of the Class B fleet and as such suggests that it does not have a noticeable effect on scallop catch.

Similar analysis was carried out on the correlation that the scallop density estimates have with the total scallop catch of the Class A fleet at locations with different levels of effort used by the Class B fleet prior to the start of the scallop fishing season. For Denham Sound no discernable patterns emerged between the correlation coefficients and the level of pre-season Class B fishing effort. Similarly, for Shark Bay North no patterns were observed between the correlation coefficients for the high, medium and low effort categories though the positive linear correlation for locations that were fished by the Class B fleet before the start of the scallop season was somewhat weaker than for locations that were not. These differences however are small and there was only a sufficient amount of data located in the Shark Bay North region to conduct this analysis for three of the six fishing seasons under consideration. Consequently, these results do not suggest that the level of pre-season fishing effort used by the Class B fleet has an effect upon the linear correlation between the estimated scallop density and the total catch of the Class A fleet.

As the data being investigated in this thesis were spatial in nature Tjøstheim's Index was used to measure the spatial association between several variables of interest. The resulting indices revealed that there was no statistically significant spatial association between the total scallop catch of the Class A fleet and the pre-season fishing effort of the Class B fleet for either region however very few seasons contained a sufficient number of common locations for a meaningful index to be calculated. The Tjøstheim's indices calculated also indicated that for both regions there was a weak to very weak spatial association between locations with a high level of Class B fishing effort and locations with a low total catch for the Class A fleet. For all but one case however these spatial associations are not statistically significant. Similarly, weak spatial associations were typically measured between locations of high total fishing effort of the Class B fleet and locations of low catch rate for the Class A fleet and these associations were usually not statistically significant. The Tjøstheim's indices also revealed that for both regions there is a weak, if any, spatial association between locations where a high level of fishing effort was used by the Class B fleet and locations with a low total scallop catch recorded for both fleets combined for almost every season and that this association is often not statistically significant. These results indicate that there is generally a weak to very weak spatial association between locations at which a high level of fishing effort was used by the Class B fleet, for either the entire season or the period prior to the scallop season, and locations that recorded a low scallop catch, for either both fleets combined or the Class A fleet individually, and that any association measured was typically not statistically significant. As such, the Tjøstheim's indices presented in this thesis do not provide evidence that fishing by the Class B fleet has a detrimental impact on the scallop catch of the Class A fleet.

Finally, the relationship between the fishing effort used by the Class B fleet during the main spawning period (May to July) and the density of recruit scallops, as estimated from the following scallop survey, was investigated within a specific area of interest located in Shark Bay North. Spatial maps of these two variables did not display any consistent patterns between the level of fishing effort and the density of recruit scallops however in a few individual cases areas of high fishing effort did correspond with locations of low recruit density. In addition to this no statistically significant linear correlations were observed between the variables and only a single season had a statistically significant Tjøstheim's Index with this particular index signifying disassociation between locations of high fishing effort and locations of low recruit density.

The results obtained from the statistical analysis presented in this thesis do not indicate that there is a marked nor consistent relationship between the level of fishing effort applied by the Class B fleet and the size of the subsequent scallop catch achieved by either the Class A fleet individually or by both fleets combined. Subsequently, this thesis has not found evidence suggesting that the fishing activity of the Class B fleet, over the entire season, during the spawning period or prior to the start of the scallop season, has a direct effect on the size of the scallop catch achieved by the Class A fleet during the 2000 to 2005 fishing seasons.

5.2. Further Discussion

Although the results presented in this thesis have not found statistical evidence of a relationship between the fishing effort used by the Class B fleet and the scallop catch of the Class A fleet, they have not proved that the fishing activity of the Class B fleet does not have an effect, directly or indirectly, on the catch achieved by the Class A fleet. It is entirely possible that further investigations using different aspects of the fishing effort of the Class B fleet and the scallop catch of the Class A fleet (or the scallop survey results) may find evidence of a relationship.

The results presented in this thesis were calculated using data that had been aggregated onto a one nautical mile regular grid. Furthermore, locations from across the entire Shark Bay fishery were used in most of the analysis. Different results may be obtained if data were aggregated onto a smaller or larger grid size and this may possibly generate more common locations between variables and allow measures such as Tjøstheim's index to be calculated in cases were it has not been used in this thesis due to an insufficient number of co-located data. Results of interest may also be achieved if the analysis used data from specific areas of concern, such as the study area discussed in Chapter 4.4., as the interaction between the fishing activity of the Class B fleet and the catch of the Class A fleet may be more acute in certain areas.

Other methods of analysing correlation and association may also be of use in studying the interaction between the Class A and Class B fleets in Shark Bay. Methods of bivariate correlation that remove the spatial trends from data, such as the Clifford and Richardson method or the method of data "prewhitening", may be useful in this situation (see Haining, R., 1991). Wong's Location-Specific Cumulative Distribution Function (LSCDF) and the associated K-S like statistic may also be helpful in studying the interaction between the two fleets as it not only indicates the magnitude of difference between two spatial distributions but can also reveal areas where these distribution have the greatest difference (Wong, D., 2001).

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Appendix

Appendix A: Level Files

A.1. Estimated Total Scallop Density

Table A1: Total scallop density estimates, levels, Shark Bay North 1999-2005 (scallops/nmil^2)

Shark Bay North	1999	2000	2001	2002	2003	2004	2005
Minimum	0.0	0.0	589.6	142.0	351.0	0.0	724.0
1st Decile	202.0	321.5	2016.9	1428.0	2301.0	697.4	1348.0
2nd Decile	752.0	2461.5	4726.2	2176.0	2986.5	3498.6	3887.9
3rd Decile	1361.0	4731.2	5941.1	3015.0	6909.0	6453.6	6205.3
4th Decile	2897.5	6335.6	7485.6	3502.0	8623.0	7787.5	8704.1
5th Decile	6741.0	7301.1	9459.8	4229.0	10307.0	9075.1	12099.8
6th Decile	8411.0	14187.3	12535.1	6282.0	12957.0	10284.4	15823.5
7th Decile	18493.0	15458.0	15839.0	9079.0	20793.0	13784.1	19887.3
8th Decile	28306.0	16776.0	24549.8	19404.0	39920.5	16812.5	24369.1
9th Decile	48761.0	28668.4	32213.9	37436.0	58334.0	25293.6	27829.7
Maximum	177793.0	68060.1	42674.1	60547.0	125440.0	33150.3	37229.3

Table A2: Total scallop density estimates, levels, Denham Sound 1999- 2005 (scallops/nmil^2)

Denham Sound	1999	2000	2001	2002	2003	2004	2005
Minimum	0.0	0.0	447.1	0.0	2482.3	3256.7	4444.7
1st Decile	0.0	0.0	1631.9	0.0	6048.3	7425.6	10937.4
2nd Decile	382.7	0.0	1917.9	205.5	8389.8	8063.4	13362.5
3rd Decile	393.3	972.6	1932.9	786.3	10569.0	11900.8	17699.3
4th Decile	510.9	2125.2	3055.1	2137.1	12710.5	17429.6	19491.0
5th Decile	695.3	2849.9	4194.6	2781.4	19582.0	19849.0	22171.6
6th Decile	1034.2	5748.6	7152.4	4903.1	23907.8	24446.6	24306.9
7th Decile	1199.8	8200.1	7723.1	7867.4	30650.3	35846.4	35345.9
8th Decile	1476.9	8376.1	15529.8	10718.7	43341.1	47813.0	38099.6
9th Decile	4745.8	13402.3	19161.2	16711.4	66295.3	76813.3	43531.7
Maximum	5230.0	18349.9	24818.3	74543.2	196617.5	138535.7	61891.4

A.2. Total Combined Class A and B Scallop Catch

Table A5: Total Combined Class A and B fleet Scallop Catch levels, Shark Bay North 2000-2005 (kg)

Shark Bay North	2000	2001	2002	2003	2004	2005
Minimum	0.0	5.5	0.0	3.3	9.2	6.0
1st Decile	18.0	24.3	25.1	12.9	15.3	12.0
2nd Decile	36.0	47.9	49.0	20.7	35.6	25.0
3rd Decile	60.0	72.0	94.6	30.7	63.1	60.0
4th Decile	90.0	114.9	138.0	45.1	106.2	84.0
5th Decile	150.0	166.0	230.9	60.9	175.2	120.0
6th Decile	228.0	235.0	331.4	88.6	253.1	154.0
7th Decile	405.0	347.6	539.4	134.4	358.3	240.0
8th Decile	960.0	552.5	867.0	217.3	560.0	348.0
9th Decile	1918.0	864.0	1435.5	420.2	1042.1	558.0
Maximum	5117.0	3401.0	8966.0	4020.6	3356.0	1967.0

Table A6: Total Combined Class A and B fleet Scallop Catch levels, Denham Sound 2000-2005 (kg)

Denham Sound	2000	2001	2002	2003	2004	2005
Minimum	1.0	3.3	8.9	11.1	11.7	24.0
1st Decile	5.0	12.6	24.2	33.4	51.7	108.0
2nd Decile	10.0	16.8	30.4	61.1	98.1	294.0
3rd Decile	12.0	24.7	49.1	96.7	158.5	444.0
4th Decile	12.0	33.5	75.5	137.2	245.0	627.0
5th Decile	12.0	54.0	102.0	189.6	400.0	969.0
6th Decile	17.0	71.7	220.0	308.9	721.0	1268.0
7th Decile	24.0	97.6	577.9	394.2	972.0	1824.0
8th Decile	24.0	168.4	957.1	615.7	1479.5	2394.0
9th Decile	36.0	364.1	1531.6	1080.0	2518.1	3309.0
Maximum	828.0	1214.1	4713.0	4952.7	7231.5	12306.0

A.3. Combined Class A and B Scallop Catch Rate

Table A7: Combined Class A and B fleet scallop catch rate levels, Shark Bay North 2000-2005 (kg/hr)

Shark Bay North	2000	2001	2002	2003	2004	2005
Minimum	0.0	1.1	0.0	1.0	1.0	1.0
1st Decile	1.2	3.0	3.0	1.8	2.4	1.6
2nd Decile	1.8	4.6	6.0	2.6	4.2	2.7
3rd Decile	2.5	6.4	7.8	3.9	6.9	3.7
4th Decile	3.4	8.4	10.1	5.3	8.8	4.7
5th Decile	5.1	10.5	11.9	7.7	10.8	6.1
6th Decile	7.3	12.3	14.4	10.4	13.1	7.0
7th Decile	11.2	14.4	17.0	12.6	16.0	8.9
8th Decile	17.0	17.5	24.1	15.6	19.7	11.1
9th Decile	24.3	24.1	35.9	28.8	28.8	16.2
Maximum	49.1	150.9	113.5	156.8	246.1	53.3

Table A8: Combined Class A and B fleet scallop catch rate levels, Denham Sound 2000-2005 (kg/hr)

Denham Sound	2000	2001	2002	2003	2004	2005
Minimum	0.1	1.0	1.2	1.2	1.1	1.7
1st Decile	0.4	1.5	1.9	2.6	4.0	5.0
2nd Decile	0.7	1.8	2.7	4.2	5.3	8.6
3rd Decile	0.9	2.5	3.3	5.9	8.3	11.5
4th Decile	1.1	3.3	5.2	7.0	10.4	15.5
5th Decile	1.2	4.2	9.3	9.1	13.9	18.7
6th Decile	1.2	5.0	16.1	10.3	18.7	24.9
7th Decile	1.4	8.1	23.4	13.5	24.9	28.9
8th Decile	1.9	10.4	29.2	30.0	32.5	35.3
9th Decile	2.4	13.2	38.4	52.3	43.5	43.6
Maximum	37.9	43.3	85.8	122.0	92.1	86.4