King Prawn Catch by Grade Category from an Economic and a Stock Management Perspective

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Abstract We give a geostatistical analysis of western king prawn logbook data collected from the Shark Bay prawn fishing fleet in Western Australia for the 2000 and the 2004 fishing seasons, aggregated into total catch, together with three weight sub-classes and grouped into lunar months. For each of the two years we discuss both the spatial correlation between the weight classes and the spatial correlation for corresponding months in the two years under consideration. Finally, we use a cost function that takes account of the different weight classes to compare the financial return by location between 2000 and 2004.

1 Introduction

In this paper we consider king prawn catch data from the Shark Bay Prawn Managed Fishery in Western Australia and carry out a comparative statistical analysis by weight classes *Small*, *Medium* and *Large* for the 2000 and 2004 fishing seasons. Firstly we analyse the numerical distribution of catch by weight class and investigate any change from 2000 to 2004 and link this to differences in fishery management practice between these years. Secondly we analyse the spatial distribution of catch by weight class and investigate differences between 2000 and 2004 in the areas where the more commercially valuable large prawns are caught. As well as spatial maps we calculate Spearman's rank correlation coefficient, Tjøstheim's index of spatial association, and cross-semivariograms. We consider both total prawn catch accumulated by location over the entire fishing season, as well as results for selected lunar months.

The Shark Bay Prawn Managed Fishery is Western Australia's most significant prawn fishery. Trawling takes place between March and October each year and fishing occurs nightly, except for a closure period around the full moon of each month (Kangas and Sporer, 2000). In addition the fishing ground is subject to a number of area closures throughout the fishing season to protect smaller prawns

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and the spawning stock. Changes in management practice between 2000 and 2004 include targeting the larger prawns and avoidance of smaller less valuable prawns. The general migration pattern of smaller prawns is in a northerly direction from the southern breeding grounds and annual research surveys of size distributions were used to implement area closures to optimise size. Our study provides an assessment of the success or otherwise of this targeting strategy as evidenced between the 2000 and 2004 fishing seasons.

2 Data Description

The data considered here are prawn catch logbook data from 2000 and 2004. The logbooks are completed on a voluntary basis by the prawn fishers. The information collected comprises the start latitude and longitude for each trawl, the effort (minutes trawled) and the catch in kilogram by grade and species. There are six grade categories (number of prawns per pound: U10, U15, U20, U25, U20-30 and U30+). In our analysis we use the weight classes *Large,* consisting of king prawns in categories U10 and U15, *Medium,* U20 king prawns, and *Small,* comprising those graded as U25, U20-30 and U30+. High catches and workload during the fishing can lead to incomplete records. Typically there are no coordinates for about 10% of the records, and for approximately 65% there is no information by trawl shot but rather on a coarser basis, such as the start latitude and longitude for the entire night together with the amount of prawns by grade. For our analysis the catch locations were converted to nautical miles and a local coordinate system with origin at 24° south latitude and 113° east longitude. Records without coordinates were eliminated from the data sets and the remaining records were aggregated to catch per square nautical mile. Two time spans were chosen, the entire fishing season and a fishing month. In order to compare the spatial patterns, only locations common to both years were considered.

The within-season time series for the total catch per month and weight class in kg and the overall effort expended in hours for 2000 and 2004 are shown in Fig. 1. The month with the maximum catch in both years was May, and in both cases the weight class whose contribution is greatest is that of medium sized prawns. This peak in May is associated with the opening of an extended nursery area in the southeast of Shark Bay. The overall catch for 2000 was higher than that for 2004. There has been little change in the shape of the time series for medium and small prawns but there is a marked change for large prawns with a clear maximum in May 2004, but a much flatter distribution in 2000.

The catch composition has changed between the two years. In 2000 medium sized prawns comprised at least 50% of the catch in the first four months of the fishing season. In 2004 the split between the three weight classes was more even in the first four months. The most marked shift is towards prawns in the larger grade categories in 2004, with a minimum contribution of 35% and a maximum of 62%, compared to a minimum of 23% and a maximum of 55% in 2000.

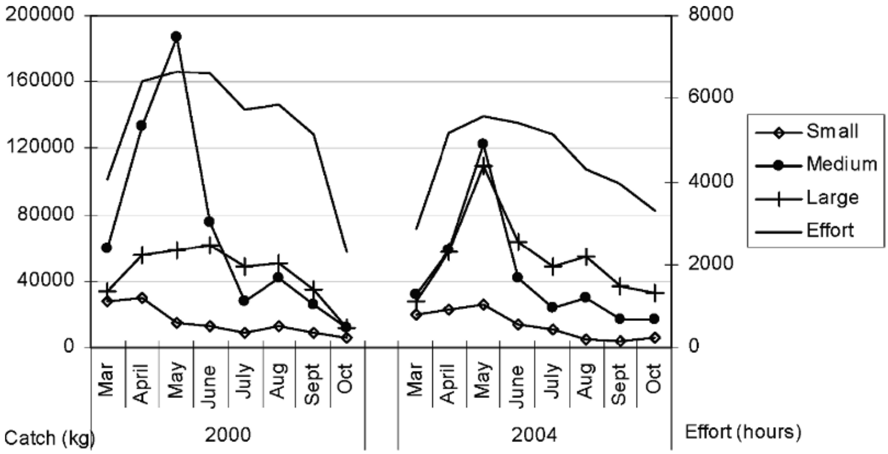

Fig. 1 Total catch per month by weight class and effort by month

The spatial distribution for the total catch over the entire year for 2000 and 2004 is shown in Fig. 2. There are two distinct fishing regions.

The region south of latitude −90 Nm is referred to as Denham Sound, the region north of latitude −90 Nm and south of −70 Nm as Peron and that north of −70 Nm as Red Cliff. For both years there is a region of high catch in the Peron fishing ground east of 26 Nm longitude. The western part of Peron appears to show greater variability, as does Red Cliff. For Denham Sound, high catches are concentrated in

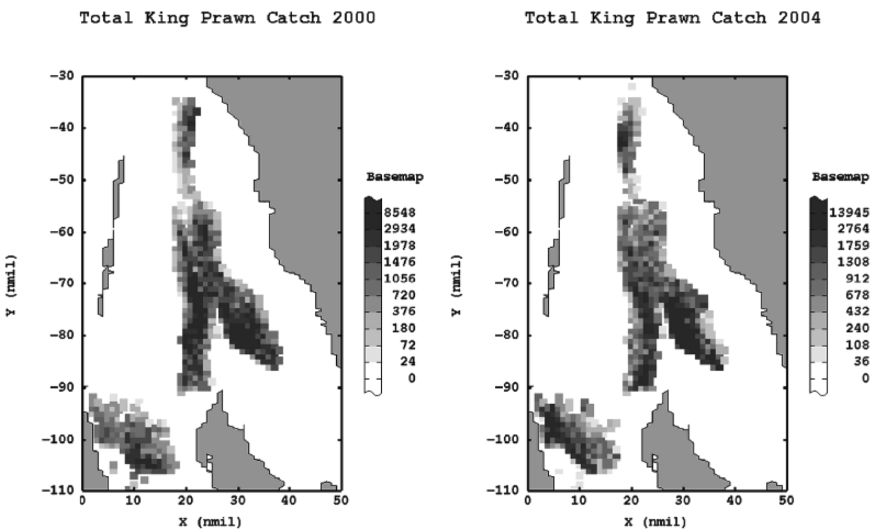

Fig. 2 Location maps (levels in deciles in kg) of the total king prawn catch in 2000 and 2004

the south-west in both years, and there is a region of high catch in the west in 2004. The spatial distribution of the effort for both years exhibits similars features.

Since the time spent fishing differs markedly between grid locations the effort needed to be accounted for in the analysis. The total amount caught per Nm^2 was converted to a standardised catch by dividing the total catch by the total effort expended in hours within the 1 Nm by 1 Nm window. The standardised catch data for the years 2000 and 2004 are moderately to strongly positively skewed (see Table 1). The relative ordering for the skewness coefficients is the same in both years with standardised small prawns being the most skewed followed by medium sized prawns and then large prawns.

Except for the large prawns the standardised catches in 2000 have greater variances. The overall means are comparable but the individual means again reflect changes in the fishing practice, whereby in 2004 the contribution of large prawns to the overall catch is almost 50% compared to 35% in 2000. The proportions of small prawns are comparable. Spearman's rank correlation coefficient for the entire region between the two years indicates a (statistically) significant positive correlation between the small and medium catch ($r = 0.2$) and medium and large catch ($r = 0.43$) in 2000. In 2004 there is significant positive correlation between any pair of variables with $r = 0.63$, $r = 0.12$ and $r = 0.53$ for small and medium, small and large and medium and large respectively. Between the years all three weight classes have significant rank correlation coefficients ($r = 0.09$, $r = 0.52$ and 0.21 for small, medium and large respectively).

The spatial distributions for the various weight classes are shown in Fig. 3 and Fig. 4. For all three weight classes, the distributions in Denham Sound have changed considerably. For small prawns low catch values are more widely dispersed in 2000 than in 2004 when the higher catches are concentrated in the east of the northern fishing region. There is a region of low catch in the central part of the Red Cliff fishing ground in 2000 which is not present in 2004. The pattern for medium and large prawns is similar between −90 Nm latitude and −50 Nm latitude, but there is little similarity north of −50 Nm.

May has the overall highest catch. Summary statistics for the standardised catch in May are given in Table 2. As already noted in the raw data, there are shifts in the size composition of the total standardised catch. The means for the total catch for the two years are comparable while the mean for medium prawns was approximately

Table 1 Summary statistics of standardised catch by weight class in 1 Nm^2 blocks, 2000 and 2004. StSm00, StSm04, StM00, StM04, StL00 and StL04 denote standardised small, medium, large catch in 2000 and 2004 respectively

	StSm00	StM00	StL00	StT00	StSm04	StM04	StL04	StT04
Mean	2.78	13.70	8.86	25.34	3.06	9.63	12.54	25.23
Variance	7.22	92.98	14.59	149.10	5.97	37.78	24.98	125.56
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.47
Median	2.18	10.93	8.46	22.62	2.56	8.02	12.02	22.83
Maximum	24.00	54.44	25.34	75.67	17.21	35.10	33.40	78.81
Skewness	2.60	1.49	0.62	1.04	1.40	1.38	0.82	1.19

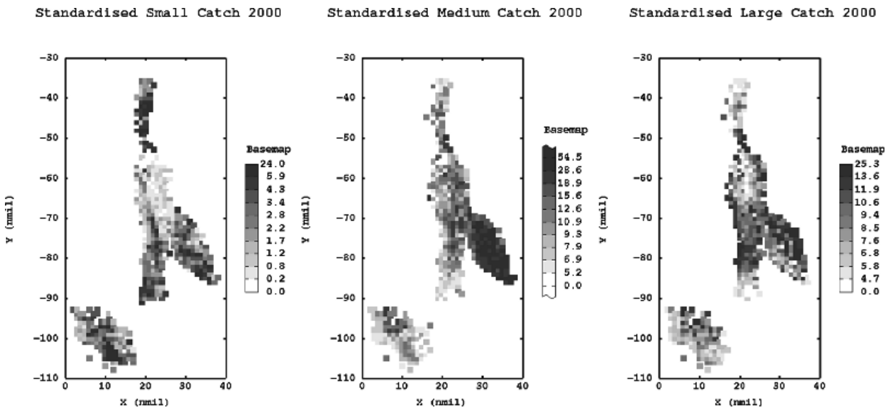

Fig. 3 Location maps (levels in deciles in kg/h) for standardised catch by weight class, 2000

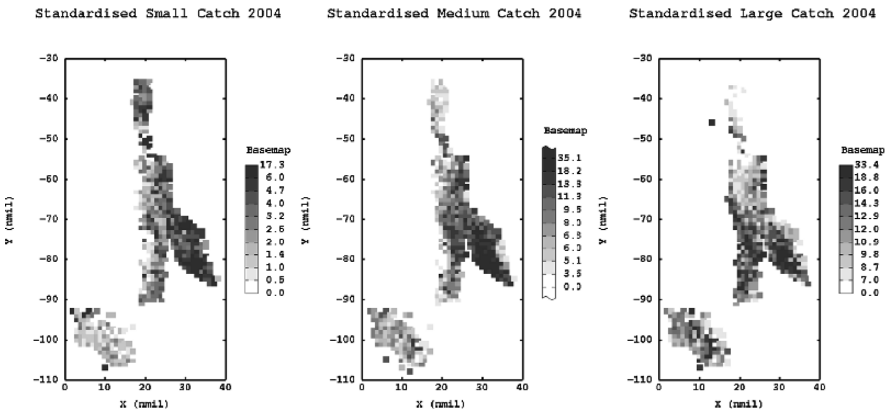

Fig. 4 Location maps (levels in deciles in kg/h) for standardised catch by weight class, 2004

30% lower in 2004. In contrast the mean for large prawns in 2000 was only approximately 60% of the 2004 mean. Apart from small prawns the data are moderately positively skewed, with the total catch in both years having the least skew.

Spearman rank correlation coefficients show a significant positive correlation between small prawn catch and the other two weight classes within the same year.

Table 2 Statistics of standardised catch by weight class, May 2000 and May 2004

	StSm00	StM00	StL00	StT00	StSm04	StM04	StL04	StT04
Mean	2.73	30.41	11.39	44.53	4.65	21.50	18.87	45.02
Variance	8.10	173.18	66.52	285.40	10.46	142.30	92.05	442.33
Minimum	0.00	2.30	0.00	4.61	0.00	0.00	1.02	1.02
Median	2.11	29.83	9.67	45.02	4.22	21.82	18.23	45.03
Maximum	19.10	66.78	35.20	93.05	15.43	59.83	48.38	115.01
Skewness	2.15	0.12	0.71	0.05	1.00	0.38	0.58	0.20

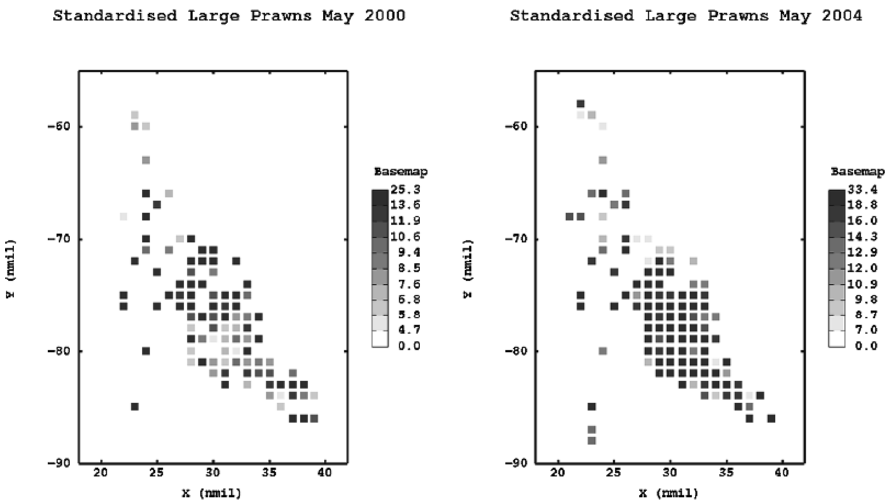

Fig. 5 Location maps (levels in deciles in kg/h) of standardised large prawn catch in May

In 2004 this was also the case for medium and large prawn catches. Between the years, Spearman's coefficient indicates significant correlation for the medium catch. In contrast to the situation for the entire year, there are no other significant associations. Location maps for the standardised prawn catch for May show that the locations of high catch between the two years differ considerably for large and small prawns, while the distributions for medium prawns are similar (see Fig. 5 for large prawns). These changes may indicate differences in the timing of recruitment and/or the growth of prawns between the years. In addition, subtle changes in real-time management between the two years may have resulted in finer scale area openings that vary between the years and may have influenced the fishing pattern.

3 Assessment of Spatial Correlation

Consideration of the spatial maps suggests that locations of high catch do not change significantly across the years. When considering monthly intervals, the spatial maps indicate that whether or not there is a change may depend on the weight class. This is also supported by changes in the statistical significance already observed when going from the annual time scale to the monthly time scale. To further test these observations several approaches were used. Experimental semivariograms and cross-semivariograms were computed to assess the similarities in the spatial structure for the weight classes between years. In particular, we check whether or not a linear model of coregionalisation can be fitted. To obtain a numerical measure Tjøstheim's index of spatial association (Tjøstheim, 1978; Hubert and Golledge 1982) was calculated. This index was used to check if it is possible to predict the position of the location ranked i for one variable from knowledge of the location ranked i for the other variable. Tjøstheim's index A is defined as

$$A = \sum_{i=1}^{n} [x_F(i)x_G(i) + y_F(i)y_G(i)]$$

where the two variables F and G are observed over the same n locations and ranked from 1 to n, and $(x_F(i), y_F(i))$ and $(x_G(i), y_G(i))$ denote the location of rank i on F and G respectively, and where the coordinates of the locations are standardised in such a way 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

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

Ties in the ranking were broken by ordering locations of equal rank first in ascending order of x then in ascending order of y. Under randomization of ranks, the index has a normal distribution with $\mathrm{E}(A) = 0$ and $\mathrm{var}(A) = (1 + r_{xy}^2)/(2(n-1))$. The quotient $A/\sqrt{\mathrm{var}(A)}$ is a test statistic to assess whether or not there is any spatial relation between the two variables.

3.1 Variography

Consideration of the semivariogram surfaces of the standardised catch for the entire fishing season indicates anisotropy for medium and total catch with major direction N-S, while large prawn catch and small prawn catch are isotropic. The anisotropy may in part be attributed to the shape of the northern fishing region. The data for Denham Sound exhibit isotropy when considered separately while for medium prawns and total catch the northern region exhibits the same spatial pattern as the overall region. However, the small prawn catch is anisotropic with major direction N-S in 2000 but is isotropic in 2004 and large prawn catch shows anisotropy in the direction of azimuth $-60°$ in 2004 and is isotropic in 2000. For large prawns the shapes of the semivariograms are spherical, but this is not the case for the cross semivariogram whose shape appears gaussian. In contrast, for the standardised medium and small prawn catch it is possible to fit linear models of coregionalisation, whether the entire, the northern region or Denham Sound is considered. For example the model for standardised small king prawn catch in the entire region is given by

$$\gamma(\mathbf{h}) = \begin{bmatrix} 3 & 0 \\ 0 & 2.3 \end{bmatrix} nug(\mathbf{h}) + \begin{bmatrix} 1.8 & 0.2 \\ 0.2 & 0.8 \end{bmatrix} spher_{3.3}(\mathbf{h}) + \begin{bmatrix} 2.3 & 0.7 \\ 0.7 & 3.5 \end{bmatrix} spher_{17}(\mathbf{h})$$

where *nug* and $spher_a$ denote the nugget effect and spherical model of range a respectively. The model fit is shown in Fig. 6. In the light of results from survey data for assessing Atlantic cod stock (Warren, 1997), which showed that an increase in relative nugget preceded the total exhaustion of the species, we note here that the relative nugget for the entire fishing season was essentially unchanged from 2000 to 2004 for both small and large prawns.

Apart from October, for which there were few samples in 2000, the monthly experimental semivariograms for corresponding weight classes in the two years have similar features, but with varying relative nugget. For both small and large prawns the relative nugget increased in May, June and August, was unchanged in April and July and decreased in March and September. For May the experimental semivariograms can be fitted by a nugget plus one spherical structure. (see Table 3 for the chosen parameters).

The quality of the fit is generally good as is illustrated by the model fit for the standardised total catch shown in Fig. 7.

The situation is more complex for the associated cross semivariograms. For March, April, September and October they show little structure. In May the cross semivariograms do not show a spherical shape so that a model of coregionalisation cannot be fitted for any of the pairs of variables between years. The cross-semivariogram of the model that produces an appropriate fit for the semivariograms of the standardised large catch is shown in Fig. 8. The behaviour exhibited here is similar for the entire year. The cross-semivariogram shows small values until a lag spacing of 10 Nm is reached, at which time a steep rise is visible.

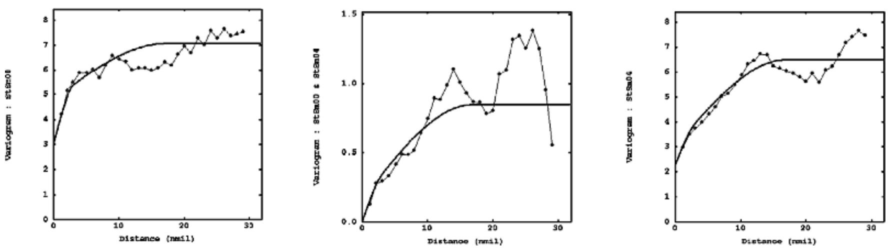

Fig. 6 Model fit for the linear model of coregionalisation for standardised small prawns

Table 3 Semivariogram model parameters, May 2000 and 2004

	2000			2004		
	Nugget	Range	Sill	Nugget	Range	Sill
StSmall	5	9.9	3	7.4	7.4	2.3
StMedium	50	5.8	102	72	8.1	67
StLarge	24	11.2	43	52	14.2	39
StTotal	47	6.6	208	240	12.6	230

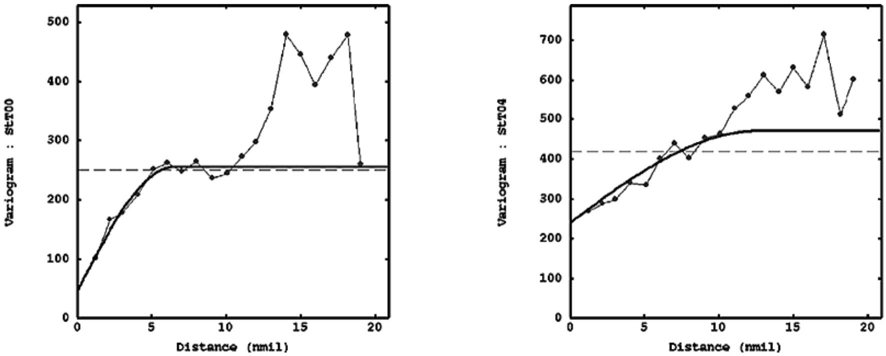

Fig. 7 Model fit for standardised total catch in May 2000 (**left**) and 2004 (**right**)

There are instances in individual months where a linear model of coregionalisation provides a good fit. Medium prawns in July (see Fig. 9) or large prawns in June provide an example where such a model does apply.

3.2 Spatial Rank Correlation

Tjøstheim's index of spatial association (see Table 4) shows that, taken across the entire year, locations of high rank for medium sized prawns in 2004 tend to be close to those of similar rank in 2000. There is no such relationship for standardised small or large prawn catch between the two years. In 2000 there was no association between the locations of high rank for small prawns with those of large or medium sized prawns, while in 2004 locations of high small prawn and medium prawn catch were associated. On the other hand, in both years there was a weak association between medium and large prawns. For May the only Tjøstheim index that is statistically significant is the one measuring the association between medium and small prawns in 2004 (A = 0.23).

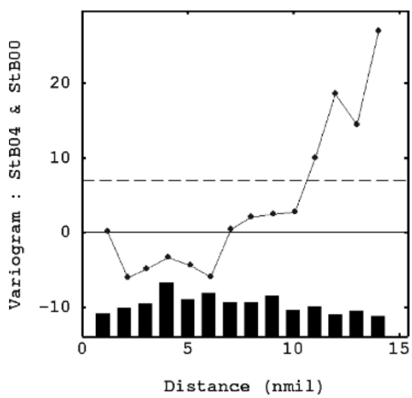

Fig. 8 Experimental cross semivariogram for standardised large prawn catch

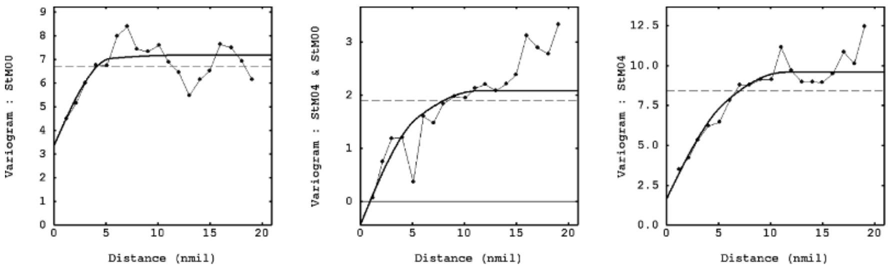

Fig. 9 Linear model of coregionalisation for standardised medium prawn catch, July 2000/2004

The commercial value of the catch varies with the weight class. An analysis of the prices for prawns indicates that if the value for medium sized prawns in set to 1 monetary unit per kg, then the appropriate values for small and large prawns are 0.75 and 1.25 respectively. The location maps for May are shown in Fig. 10.

Table 4 Tjøstheim's indices for standardised small, medium and large catch in 2000 and 2004, * indicates the value is significant at the 0.05 level

Tjøstheim	StSm00	StM00	StL00	StSm04	StM04	StL04
StSm00	–	0.00	0.02	−0.01	–	–
StM00		–	0.07*	–	0.11*	–
StL00			–	–	–	0.02
StSm04				–	0.17*	−0.04
StM04					–	0.10*
StL04						–

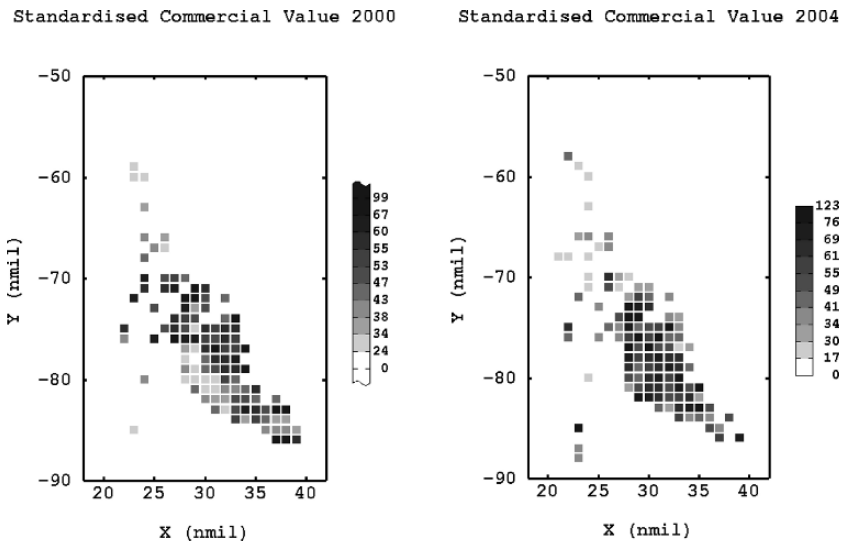

Fig. 10 Standardised commercial value of king prawn catch, May 2000 and 2004

The spatial distribution of the economic value of the catch for the entire year in Peron and Red Cliff has changed little between 2000 and 2004, but there were considerable changes in Denham Sound. This is also confirmed by the value of Tjøstheim's index for Peron and Red Cliff whose value of 0.13 is significant at the 0.01 level of significance, while that for Denham Sound (0.01) is not significant. For May Tjøstheim's index for the standardised commercial values is −0.12 indicating a lack of coincidence of locations with equally ranked financial returns for the two years, this may be visually confirmed in Fig. 10.

4 Conclusions

In summary, while annual variation in the timing and strength of recruitment of king prawns may result in shifts in overall size distributions from year to year, the spatial structure of the catch distribution is not affected. Also, there are no major changes in the spatial continuity for the individual weight classes from year to year. There are slight changes in the range and variations in the relative nugget but the shapes of the semivariograms do not change. Similarly, apart from the start and the end of the fishing season, the semivariogram structures in corresponding months of the two years are comparable. However, there is no evidence that equally ranked values for different weight classes occur at the same locations within one year and high values of large catch and high values of small catch are not co-located due to the clear migration pattern of smaller prawns in Shark Bay moving from south to north. The higher proportion of larger individuals retained in 2004 indicates that targeting larger prawns as a strategy is working, with the management arrangements protecting small prawns as intended. This in turn will result in economic benefits to the industry due to the higher value of larger prawns.

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