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The delineation of fishing times and locations for the Shark Bay scallop fishery

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1 Introduction

In this paper we use scallop survey data and lognormal ordinary kriging (Chiles and Delfiner 1999) to obtain a spatial mapping of estimated scallop density in the Red Cliff and NW Peron regions of the Shark Bay managed scallop fishery in Western Australia. The results can then be used, together with the annual pre-season scallop survey, to inform the management decision as to the opening time of the subsequent scallop fishing season.

The Shark Bay Scallop Fishery is Western Australia's largest scallop fishery. Its outer boundaries encompass the waters of the Indian Ocean and Shark Bay between 23°34' south latitude and 26°30' south latitude and adjacent to Western Australia on the landward side of the 200 m isobath, together with those waters of Shark Bay south of 26°30' south latitude (Department of Fisheries 2002).

The scallop catch depends primarily on the strength of recruitment from the breeding season of the previous year. Spawning commences in mid-April and meat condition declines as spawning continues, so the process of setting the opening date of the season needs to balance breeding stock and the seasonal decline in meat condition. In order to determine the opening date for the fishing season a pre-season survey is conducted in November and December of the previous year. The survey covers the three fishing regions Red Cliff, NW Peron, and Denham Sound but, as there has been little fishing activity in Denham Sound during the years considered, only the Red Cliff and NW Peron regions are used.

2 The survey data

The survey data we considered are for the years 2000 to 2003. The fishing grounds Red Cliff and NW Peron are adjacent and are treated by the Department of Fisheries, Western Australia as one fishing ground for stock prediction and we treat them in the same manner here. Each survey was carried out by FRV Naturaliste, equipped with two six-fathom headrope nets. The combined fishing ground is north of 25°30' south latitude and south of 24° 40', with the Red Cliff survey locations lying north of 25°10' south latitude. For our analysis the locations were converted to nautical miles and a local coordinate system with origin at 24° south latitude and 113° east longitude was chosen. A map of the three fishing grounds together with the survey locations is shown in Fig. 1. The area outlined in grey shows the region for which estimates were computed.

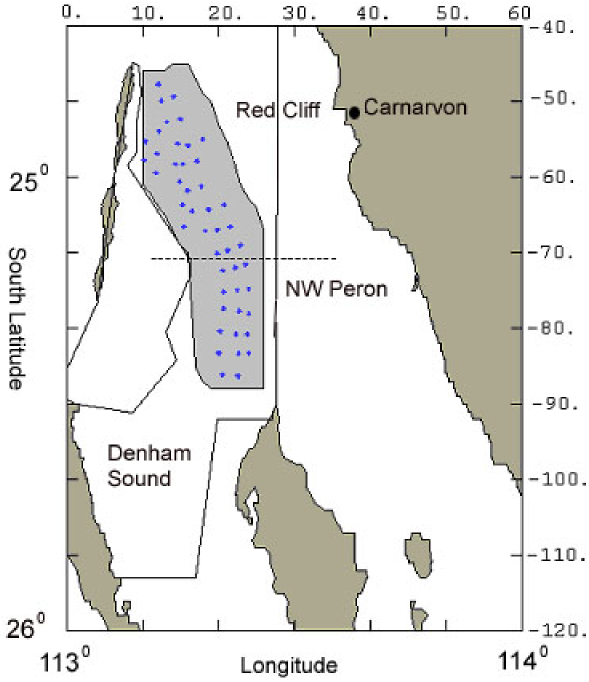

Fig. 1. Shark Bay scallop fishery, the dots indicate survey locations, the legends on the right and on the top give distances in nautical miles relative to the chosen origin

The data comprise the fishing ground, the longitude and latitude in degrees of the start and end locations of each trawl, the counts of recruit and residual scallops caught per net, the trawl duration, distance and speed. The number of survey locations varies from year to year. The numbers, giving the regional split, are shown in Table 1.

Table 1. Number of sample locations by year and data set

Fishing Ground	2000	2001	2002	2003
Red Cliff	23	18	33	30
NW Peron	19	12	12	17

The number of residuals and recruits caught per trawl and net were aggregated into total number of residuals and recruits per trawl respectively. As the trawling speed influences the efficiency of the trawl gear, the catch (by category and total) was standardised to the equivalent catch at a speed of 3.4 knots

$$c_{st} = \frac{c}{3.2331 - 0.6485v}. \tag{1}$$

Here v, c and c_{st} denote the trawl speed in knots, the catch and the standardised catch respectively. This formula was derived via a combination of practical experience to decide on a suitable adjustment factor and a subsequent linear regression of this adjustment factor on trawl speed (J. Penn, unpublished) and is deemed reliable by the Department of Fisheries, WA. For this study the standardised number of residuals, recruits and total number of scallops were converted to densities according to

$$d = \frac{c_{st}}{2Tw}, \tag{2}$$

where T and w denote the trawl distance and the width per net in nautical miles.

The scallop density distributions are highly positively skewed with the 2003 residuals density and 2002 recruits density the most strongly skewed (see Tables 2 to 4).

Table 2. Descriptive statistics of the density of residuals

Residuals Density	2000	2001	2002	2003
Mean	3641	3057	1717	5621
Standard Deviation	7054	3288	1941	13349
Minimum	0	143	0	0
Lower Quartile	0	814	314	713
Median	336	2016	991	2180
Upper Quartile	3960	4470	2539	5013
Maximum	33272	14564	7065	89610
Skewness	2.9	2.1	1.5	5.7

Table 3. Descriptive statistics of the density of recruits

Recruits Density	2000	2001	2002	2003
Mean	9117	10404	14817	17233
Standard Deviation	10561	9619	31808	21117
Minimum	0	369	0	0
Lower Quartile	1555	3848	1428	2382
Median	5865	6737	3541	7784
Upper Quartile	14425	15573	14856	24143
Maximum	55347	34101	196560	86739
Skewness	2.5	1.3	5.0	1.6

A comparison of the mean densities for recruits and residuals during the four years shows that residuals comprise respectively 29, 23, 10 and 25 percent of all scallops caught in the combined Red Cliff and NW Peron fishing region.

Table 4. Descriptive statistics of the density of total scallop catch

Total Scallop Density	2000	2001	2002	2003
Mean	12758	13461	16534	22853
Standard Deviation	14524	11444	32973	27344
Minimum	0	590	142	351
Lower Quartile	3382	5314	2750	6345
Median	7067	9460	4456	10568
Upper Quartile	16576	20906	17192	33097
Maximum	68060	42674	203626	125440
Skewness	2.2	1.1	4.0	2.0

Spatial maps for the densities of residuals, recruits and total catch for Red Cliff and NW Peron for the year 2001 are shown in Fig. 2. There are more locations with high residuals density in the Red Cliff fishing ground than in NW Peron fishing ground. For recruits the locations of high density are more evenly distributed through the two fishing grounds and the locations of low density lie in the centre of the fishing ground. Locations of high density of residuals are not co-located with those of high recruit density. Overall residuals density values are much lower than recruits densities.

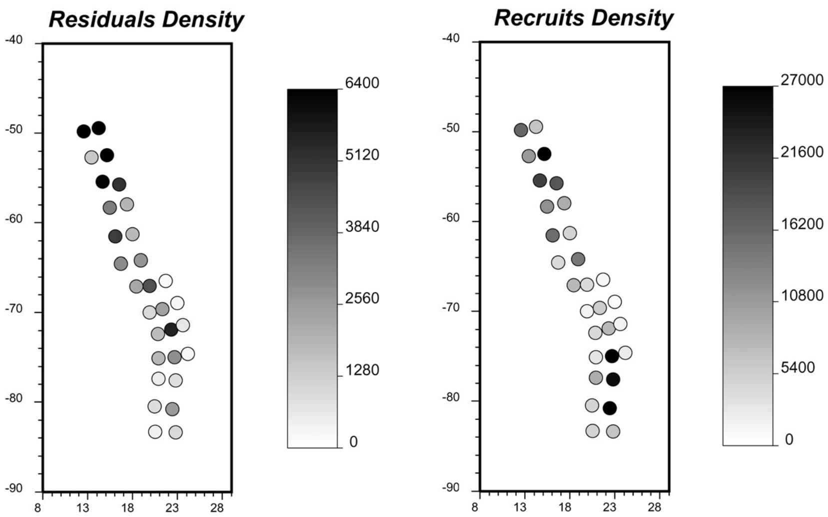

Fig. 2. Spatial maps of residuals density and recruits density 2001

The density patterns for recruits and residuals change from year to year indicating variable settlement patterns in these areas. In 2000 residuals scallop density was highest in the central part of Red Cliff and was low in NW Peron and the northern part of Red Cliff. In 2002 residuals scallop density was low to moderate in NW Peron, high at the western rim of Red Cliff, and low at the eastern rim of

Red Cliff. In the year 2003 the density distribution was similar to that in 2002 except for the occurrence of a high density patch in the south east of NW Peron.

In the year 2000 high recruits densitiy occurred throughout most of the western part of the combined fishing ground, with low density along the eastern rim. In 2002 recruits density was highest in the north west close to the permanent closure area and low throughout NW Peron. In 2003 recruits density in the north west were similar to (and greater in absolute terms than) those in 2002. Values in the NW Peron ground were low overall compared with the rest of the study region with the exception of two locations with high density in the centre.

The spatial distributions of the annual total scallop survey density for each of the four years are strongly influenced by the recruits distributions and follow similar patterns.

3 Estimation

Three-parameter lognormal ordinary kriging was used to obtain estimates for the densities of the three variables. We denote by $y(\mathbf{u})$ the lognormal variable obtained from the attribute $z(\mathbf{u})$ by putting $y(\mathbf{u}) = \ln[z(\mathbf{u}) + c]$, with c being an added constant. In each case the constant was chosen so that the transformed variable follows a normal distribution at the 5% level of significance. The constants for the specific distributions are given in Table 5.

Table 5. Added constants for lognormal distributions

Variable	2000	2001	2002	2003
Residuals	25	1	100	10
Recruits	1500	1	150	50
Totals	2000	1	0	0

The corresponding random variable will be denoted by $Y(\mathbf{u})$. The estimate for the natural logarithm of the value of the attribute at the unsampled location $\mathbf{u}$ may be expressed as

$$y^*(\mathbf{u}) = \sum_{i=1}^{n(\mathbf{u})} \lambda_i(\mathbf{u}) y(\mathbf{u}_i), \tag{1}$$

where $n(\mathbf{u})$ denotes the number of data near $\mathbf{u}$, and $\lambda_j(\mathbf{u})$ denotes the ordinary kriging weight of the j-th nearby sample. The estimate $z^*(\mathbf{u})$ is then obtained from the logarithmic estimate $y^*(\mathbf{u})$, the ordinary kriging variance $\sigma_Y^2(\mathbf{u})$ and the Lagrange multiplier $\mu(\mathbf{u})$ by

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

with variance

$$\hat{\sigma}^2(\mathbf{u}) = \exp(\sigma_Y^2(\mathbf{u}))(1+\exp(-(\sigma_Y^2(\mathbf{u})+\mu(\mathbf{u})))(\exp(-\mu(\mathbf{u}))-2)) . \quad (3)$$

Spherical models were fitted to the experimental semivariograms. The parameters used in the estimation are summarised in Table 6.

Table 6. Variogram model parameters for the variables (residual, recruit, total)

	2000	2001	2002	2003
Nugget	(0, 0.4, 0.4)	(0.5, 0.2, 0.28)	(0.3, 0.38 0.36)	(0.39, 0.99, 0.7)
$Sill_1$	(6.1, 0.42, 0.42)	(0.2, 0.7, 0.8)	(1.2, 0.53, 0.92)	(2.36, 1.59, 0.95)
$Range_1$	(13, 4.6, 4.6)	(5, 4, 5.3)	(4.8, 2.4, 5.3)	(6.3, 5.3, 4.6)
$Sill_2$		(0.62, 0.28, 0)	(0, 1.53, 0.7)	
$Range_2$		(17, 8.4, 0)	(0, 10.9, 8.6)	

The experimental semivariograms for the residuals and recruits density of 2001 and the corresponding models are shown in Fig. 3. In each case the sample variance has been chosen as the total sill.

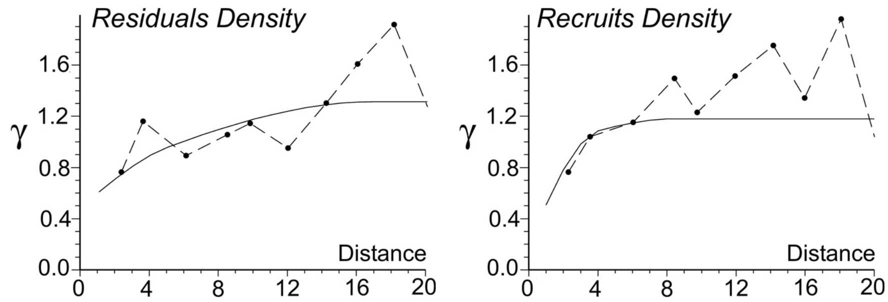

Fig. 3. Experimental semivariograms and models for residual and recruit density 2001

Cross validation results for lognormal kriging using these models are given below. From Table 7 it can be seen that the mean errors for all three variables are close to 0, there is greatest variability in the errors for the residuals density in 2000 and for all densities in 2003.

Table 7. Cross validation results for lognormal kriging

Density	Statistic	2000	2001	2002	2003
Residuals	Mean Error	0.078	0.035	-0.006	0.070
	Variance	2.130	1.04	0.970	2.073
Recruits	Mean Error	0.021	0.071	0.035	0.113
	Variance	0.973	1.124	1.188	2.638
Total Catch	Mean Error	0.023	0.071	0.052	0.087
	Variance	0.876	1.029	0.918	1.984

From Table 8 it can be seen that, with the exception of the results for 2002, the mean square error exceeds the mean kriging variance. The results are typically worse for the residuals density with the mean square error exceeding the mean kriging variance by 48%.

Table 8. Crossvalidation results for lognormal kriging, MSE/$\overline{\sigma}_Y^2(\mathbf{u})$

Density	2000	2001	2002	2003
Residual	1.48	1.35	0.96	1.11
Recruit	1.26	1.24	0.91	1.17
Total Catch	1.18	1.25	0.86	1.30

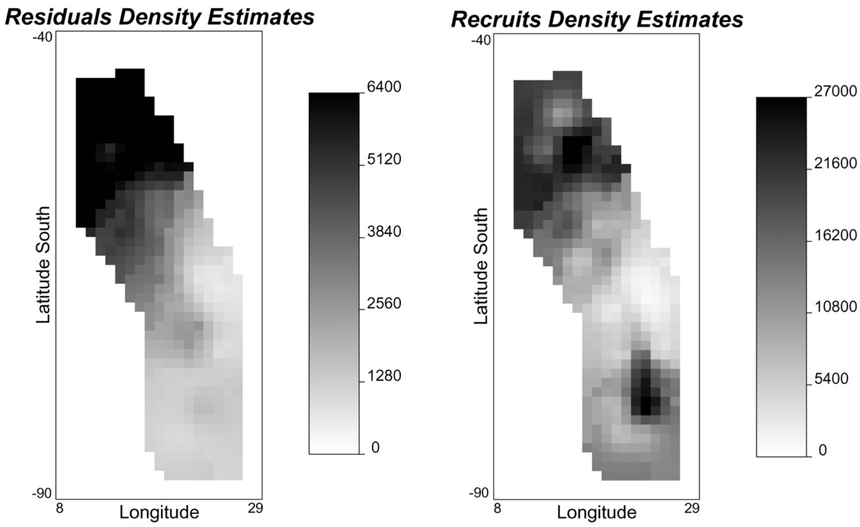

Fig. 4. Estimates of residual density and recruit density 2001

Spatial maps of the density estimates for residuals, and recruits for 2001 are shown in Fig. 4. They exhibit trends similar to those of the sample location maps discussed earlier. In all four years, there was a region of high residuals density in the Red Cliff ground. For the years 2000 and 2001 the residuals density in NW Peron was low. In 2002 and 2003 there was a different pattern in this part, with some high densities emerging in the south east. For recruits there were locations of high density in the south-east of the NW Peron ground in 2000 and 2001. In the remaining years the density was greatest in Red Cliff. Similar trends prevailed for the total catch density. The mean, standard deviation and skewness for the estimates are given in Table 9.

Table 9. Abridged descriptive statistics of the density estimates

Density	2000	2001	2002	2003
Residual				
Mean	3658	3718	1774	6670
Standard Deviation	5902	2934	1368	9295
Skewness	2.20	0.84	1.32	2.89
Recruit				
Mean	10118	12769	11075	22540
Standard Deviation	5775	6944	18180	16218
Skewness	1.15	0.23	3.17	0.95
Total Scallop				
Mean	14389	16464	12713	26062
Standard Deviation	7727	9275	18865	16791
Skewness	0.73	0.36	3.41	1.49

Except in the year 2002, when the proportion of residuals was 14%, the contribution of residuals to the expected total catch was approximately 25%. In all four years the expected total number of scallops in the Red Cliff ground was greater than that for NW Peron (see Table 10). This feature was particularly pronounced in the year 2002, where the total number of scallops in NW Peron was 12% of the estimated number of scallops in the combined Red Cliff and NW Peron ground. In the remaining years the percentage fluctuated about the 30% mark.

Table 10. Estimated percentage of scallops by fishing ground

	2000	2001	2002	2003
Red Cliff	66%	72%	88%	69%
NW Peron	34%	28%	12%	31%

4 Prediction of catch

Currently prediction of the expected annual scallop catch is based on a regression of the actual catch of previous years against the scallop index of the corresponding survey years (Joll and Caputi 1995). The scallop index is computed as the average standardised (as in Eq. (1) of Sect. 2) survey catch in the combined NW Peron and Red Cliff ground. The index treats Red Cliff and NW Peron as a whole and differences in the index between the two fishing grounds are disregarded. The predicted catches for the following years are used to set the opening date for the fishery. If predicted catch is high, an early opening date is set, while for low expected catch a late opening date is chosen. From Table 10 in Section 3 it is apparent that scallop density in the Red Cliff ground is higher than in NW Peron, even though there may be local more dense pockets in NW Peron, as was the case in 2000 and 2001. This may indicate a need to treat NW Peron and Red Cliff separately when setting the opening date.

The contributions to the expected total catch by size class for the two grounds are given in Table 11. In Red Cliff the expected contribution of recruits to the total catch exceeded 70% except in 2000 and in NW Peron this was the case in 2000 and 2001. Setting of the opening date could be further refined by taking into account the percentage contribution of recruits and residuals to the total catch by fishing ground.

Table 11. Expected percentage of scallops by size class and fishing ground

Year	RCRec	RCRes	NWPRec	NWPRes
2000	63	37	95	5
2001	73	27	88	12
2002	90	10	59	41
2003	80	20	68	32

RCRec=Recruits, Red Cliff, *RCRes*=Residuals, Red Cliff, *NWPRec*=Recruits, NW Peron, *NWPRes*=Residuals, NW Peron

To derive a method of setting the opening date based on the spatial estimates for the two size classes, we define abundance as large, if the expected percentage lies above 70%, moderate if it lies between 30 and 70% and small otherwise. The spatial maps of recruits and residuals densities for 2001 in Fig. 5. show this classification for each location.

Fig. 5. Spatial maps of residuals, recruits and expected total catch classified as high (above 70^{th} percentile, low (below 30^{th} percentile) or moderate (between 30^{th} and 70^{th} percentile)

First, the current practice scallop index could be used to determine if the expected catch is to be classed as high, moderate or low to decide on an early or late opening date. Then the opening date can then be adjusted to take into account the relativities between the two size classes. A template indicating possible decisions is shown in Table 12.

Table 12. Possible refinement startegy for setting opening dates

Recruits \ Residuals	High	Moderate	Low
High	open earlier	no change	no change
Moderate	open earlier	no change	open later
Low	open earlier	no change	open later

For the year 2002 the use of this method would have led to an early opening in the north, the opening at the time indicated by the index in the centre and a later opening date than derived from the index in NW Peron.

5 Comparison with actual catch

Fourteen boats with class A licenses (scallop only) and 27 with class B licenses (scallop and prawn) are eligible to fish for scallops in Shark Bay. The annual catch is highly variable, and ranged from 121 to 4414 tonnes meat weight in the last 20 years (Department of Fisheries 2002). The total tonnage of scallops caught in Red Cliff and NW Peron is given in Table 13 together with the contribution from the scallop fleet.

Table 13. Total scallop catch in tonnes meat weight (percentage contribution of scallop fleet to total catch in brackets)

	2001	2002	2003
All boats	205	264	54
Scallop boats	83.3 (41%)	163.3 (62%)	24.8 (45%)

The catch data (in tonnes meat weight) discussed here are those for the scallop-only fishing fleet. For each datum the position at the start of the trawl, the number of shots (a shot is the activation of the trawl gear), the total duration, the total meat weight and the date of the trawl were recorded. For the purposes of this study the temporal aspect was ignored. The duration of the scallop fishing season ranged from 2 weeks in 2003 to 6 weeks in 2001. The actual area fished by the scallop fleet varied from year to year and comprised 30% of the total available area in 2001, 14 % in 2002 (Kangas and Sporer 2002, 2003) and 4 % in 2003 (Kangas, pers. comm.). Consideration of the catch locations of the scallop fleet for 2001 to 2003 indicates that there was a tendency for the scallop fishing fleet to concentrate in the Red Cliff ground. In fact, in 2001 and in 2003 it was the case that 93% of all trawls fell within Red Cliff. In 2002 this percentage was 88%.

In 2001 part of the area fished was not contained within the region for which density estimates were derived using the survey locations, but lay closer to the coast. For a qualitative comparison of the commercial catch data with the density estimates only data with locations in the estimation grid were considered. The catch was converted to a catch per unit effort measure with the unit time set equal to the duration to the survey trawl (i.e. 20 minutes). The summary statistics for the catch per unit effort for the years 2001 to 2003 are given in Table 14. The number of shots in 2003 is much smaller reflecting the shorter duration of the scallop fishing season in Shark Bay.

Table 14. Descriptive statistics, catch per unit effort (kg/20 min)

	2001	2002	2003
Mean	6.6	8.0	34.1
Standard Deviation	13.6	8.8	58.8
Minimum	0.6	0	0.7
Median	3.8	4.87	15.0
Maximum	151. 7	78.4	344
Count	287	531	42

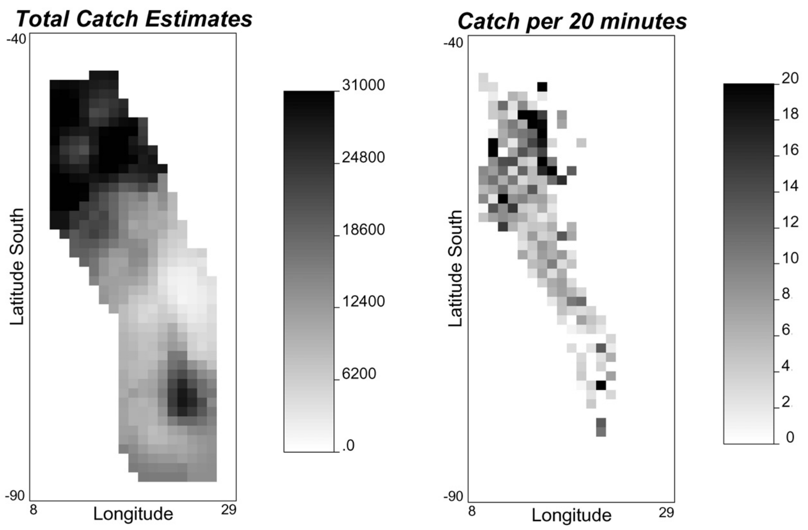

Fig. 6. Spatial maps of total catch density estimates 2001 and catch per unit effort per square nautical mile 2002

The catch per unit effort data were further standardised by moving windows to represent mean catch per unit effort per square nautical mile. The spatial maps of the expected total catch for 2001 and the subsequent (2002) fishing season are shown in Fig. 6 and indicate that the estimates derived from the survey adequately predict locations of large abundance.

6 Concluding discussion

In this paper our objective has been to analyse scallop survey data to help inform fishery management decisions on fishing opening times for the Red Cliff and NW Peron fishing regions. We have seen that the scallop survey data are amenable to analysis by intrinsic geostatistics and we have been able to identify substantial differences in both scallop settlement and scallops-only boats fishing behaviour between the Red Cliff and NW Peron fishing regions and to question the assumption that the results from these two regions be taken together when deciding on the starting date and length of the scallop fishing season. In addition, spatial maps of residuals and recruits density estimates were seen to open up possibilities for the refinement of current practice for setting the opening date for the scallop fishery.

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