A catch rate-environment time series approach to the prediction of catches taken from the Esperance southern rock lobster fishery

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Abstract: Catches for the southern rock lobster fishery in the Esperance area (120°E to 125°E) of Western Australia are a challenge to predict. Southern rock lobsters at the puerulus stage are difficult to find, and a stock assessment is economically infeasible. The CPUE series for the fishery has varied widely between 0.50 and 1.17 kg/pot lift in the past. The fishery has experienced catch rates of below 0.91 kg/pot lift for the past eight seasons. This paper explores the possibility of catch prediction using existing monthly catch and fishing effort data from relevant fishing regions in South Australia and Western Australia, and an environmental variable. We show that annual catches are highly correlated with lagged interactions involving catch rate data in May from the central area of the northern zone of the South Australian southern rock lobster fishery and a yearly moving average of the Fremantle Sea Level indicator. The formulation emulates the biological possibility that larvae may be transported from South Australian waters to the Esperance area during a one to two year timeframe. Monthly catches are predicted using a seasonal ARIMAX model, where the transfer function is defined by the annual nonlinear regression specification. The model is validated by forecasting the latest three fishing seasons (1999/2000 to 2001/2002) of catches. The transfer function component is highly significant for the seasonal ARIMAX model. Further techniques to enhance the error forecasts and to face the problem of negative 95% confidence interval limits are discussed.

Keywords: *Time series; ARIMAX; Nonlinear regression; Fishery*

1. INTRODUCTION

One of the main issues concerning the southern rock lobster (*Jasus edwardsii*) fishery off the Western Australian coast is the absence of puerulus index data as a biological predictor of annual catches. Catches of the WA southern rock lobster fishery are taken from November to June along the south coast of WA, with peak fishing occurring from December through February. Reliable data dates from 1975/76 to 2001/02; less reliable data dates back to 1968/69. Catches are greatest in the Esperance area, defined from 120°E to 125°E. A plot of historical annual southern rock lobster catch data from the Esperance area of the Western Australian fishery reveals significant time trends (Fig. 1). Annual catch-per-unit-effort (CPUE) data for the Esperance fishery exhibit a widely fluctuating distribution with a decreasing trend over the last eight years (Fig. 1). Time-lagged monthly catch rates measured from the Esperance fishery cannot explain the variation in annual CPUE data in Esperance. We therefore seek to explain annual catches adjusted for fishing effort by dynamically constructed catch rate-environment indices from South Australia. Lagged monthly catch rates may indicate annual variations in spawning activity from relevant regions in South Australia. Environmental data provide information on currents, wind speed and other effects on larval recruitment.

It is hypothesized that a proportion of the recruitment of Jasus edwardsii in the Western Australian fishery is likely to be independent of the WA brood stock (Melville-Smith, 1999). Upon inspection of the South Australian fishery data, which is available for as many seasons as the Western Australian data, we found that the central northern zone of South Australia (Fig. 2) is a good candidate for recruitment. The bulk of the southern rock lobster catches in the northern zone of the South Australian fishery is also taken from the central region. The duration of larval development for southern rock lobsters near New

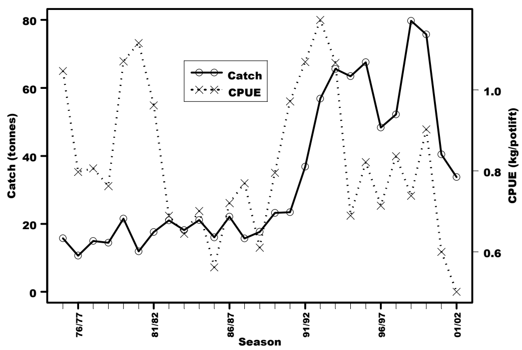

Figure 1. The annual southern rock lobster catch and CPUE series from 1975/76 to 2001/02 for the Esperance area.

Zealand is said to be at least 12-22 months (Lesser 1978, Booth 1994). Research by Pashkin (1968) and Natarov and Pashkin (1968) indicated that winter currents could direct larvae from the northern zone of South Australia across the Great Australian Bight to the Esperance area during certain years.

The focus of this paper is the modelling of annual and monthly catches of the southern rock lobster in the Esperance area using nonlinear regression and ARIMA transfer function time series analysis, respectively. The annual models are derived on the basis of fisheries science theory, combining fishing effort data with lagged monthly catch rates and environmental data.

2. METHODS

Following the methodology of DeLury (1947, 1951), a theoretical annual catch-abundance-effort equation is

$$C_t = N_t\left[1-\exp\left(-qE_t\right)\right]+\varepsilon_{1t}\,, \qquad (1)$$

where C_t is the catch subject to abundance N_t and fishing effort E_t in season *t* (available from 1975/76 to 1998/99), $q \in R$ is a catchability estimate and $\varepsilon_{1t} \sim N\left(0,\sigma_1^2\right)$. Finding initial points generally makes *q* difficult to estimate, so a fourth order Taylor series approximation in $\left(qE_t\right)$ of (1) is used, viz.

$$C_t = N_t qE_t \exp\left(-\frac{q}{2}E_t+\frac{q^2}{24}E_t^2\right)+\varepsilon_{2t}\,, \qquad (2)$$

where $\varepsilon_{2t} \sim N\left(0,\sigma_2^2\right)$. Another advantage of (2) is that the nonlinear component can be dropped if *q* is not significantly different from zero. For *q* small in magnitude, the estimation becomes linear in $\left(qE_t\right)$, viz.

$$C_t = N_t qE_t + \varepsilon_{3t}\,, \qquad (3)$$

where $\varepsilon_{3t} \sim N\left(0,\sigma_3^2\right)$. Since N_t is unknown, (3) is more parsimonious than (2). (3) is a first order Taylor approximation of (1).

Estimation of N_t is the next consideration of the model formulation. We assume a Beverton-Holt mortality function over an l to $\left(l+j\right)$ year time lag $\left(j>0\right)$, where data availability restricts us to only consider $j=1$ for the analysis in this paper, viz.

$$E\left[N_t\right]=\frac{\alpha N_{t-l}^*}{bN_{t-l}^*+1}\,. \qquad (4)$$

Here, $E\left[N_t\right]$ is the expectation of N_t, α and b are parameters to be estimated, and N_{t-l}^* is a population abundance estimate lagged l and $\left(l+1\right)$ years. Much of the relevant environmental information is contained in the Fremantle Sea Level (Pearce and Phillips, 1988), denoted S_t, which is calculated as a yearly aggregate of the monthly data. It is thus proposed that the Fremantle Sea Level is an indicator of environmental factors on the first year of larval life of a southern rock lobster caught in Esperance. A model for N_{t-l}^* is therefore

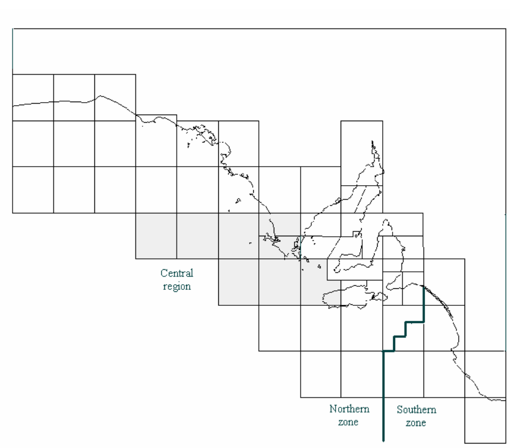

Figure 2. Map of the northern fishing zone of South Australia.

$$
E\left[N_{t-l}^{*}\right]=\cos^2\varphi\cdot C_{t-l,SA}\ \exp\left(\omega_{SA}S_{t-l}\right)\Big/
\left\{E_{t-l,SA}\exp\left(-\frac{q_{SA}}{2}E_{t-l,SA}+\frac{q_{SA}^2}{24}E_{t-l,SA}^2\right)\right\}
+\sin^2\varphi\cdot C_{t-(l+1),SA}\ \exp\left(\omega_{SA}S_{t-(l+1)}\right)\Big/
\left\{E_{t-(l+1),SA}\exp\left(-\frac{q_{SA}}{2}E_{t-(l+1),SA}+\frac{q_{SA}^2}{24}E_{t-(l+1),SA}^2\right)\right\}. \quad (5)
$$

$C_{t,SA}$ and $E_{t,SA}$ are monthly catches and fishing efforts, in season t, respectively, taken from one or a combination of the western, central or southern areas of the northern zonal fishery of South Australia. The selection of region and month, or combinations of months, is based on the best correlation between those catch rates and the total catches in l to $(l+1)$ years henceforth. φ describes the year-class proportion for lobsters originating from the chosen area of the northern zone of South Australia. ω_{SA} describes the strength of the effect of the Fremantle Sea Level average on the catches. The denominators in (5) are expressed in parsimonious form in the same way that (2) approximates (1). q_{SA} is therefore a nonlinearity parameter to be estimated.

The model that is used to describe catches of southern rock lobster in the Esperance area is thus

$$
C_t = aE_t\exp\left(-\frac{q}{2}E_t+\frac{q^2}{24}E_t^2\right)\times
f\left[\begin{array}{l}
\cos^2\varphi\cdot C_{t-l,SA}\exp\left(\omega_{SA}S_{t-l}\right)\Big/ \\
E_{t-l,SA}\exp\left(-\frac{q_{SA}}{2}E_{t-l,SA}+\frac{q_{SA}^2}{24}E_{t-l,SA}^2\right)+ \\
\sin^2\varphi\cdot C_{t-(l+1),SA}\exp\left(\omega_{SA}S_{t-(l+1)}\right)\Big/ \\
E_{t-(l+1),SA}\exp\left(-\frac{q_{SA}}{2}E_{t-(l+1),SA}+\frac{q_{SA}^2}{24}E_{t-(l+1),SA}^2\right) \\
;b
\end{array}\right]
+\eta_t, \quad (6)
$$

where

$$
f(x;b)=\frac{x}{bx+1} \quad (7)
$$

is the Beverton-Holt mortality formulation and $\eta_t \sim N\left(0,\sigma^2\right)$. Following the methodology of Box and Jenkins (1976), a seasonal autoregressive integrated moving average transfer function (SARIMAX) model is used to fit the monthly catches for the southern rock lobster fishery in the Esperance area, viz.

$$
c_{tm} = g\left(E_t,S_t;a,b,\varphi,q,\omega_{SA},q_{SA}\right)+\zeta_{tm}. \quad (8)
$$

Here, c_{tm} is the monthly catch in fishing season t (available from 1975/76 to 1998/99) and month m (from November to June). g is the (annual) expectation of (6) replicated over the eight fishing months of season t. The parameter a becomes the transfer function coefficient. The other parameters defining g are estimated using (6). ζ_{tm} are seasonal ARIMA (SARIMA) errors defined as

$$
\zeta_{tm} = \frac{\Theta\left(B^8\right)\theta(B)}{\nabla_8^D\nabla^d\Phi\left(B^8\right)\phi(B)}\xi_{tm}. \quad (9)
$$

where ϕ,θ,Φ and Θ are polynomials of finite order p, r, P and R, respectively, of the backward difference operator B, defined by $B(\cdot_t)=\cdot_{(t-1)}$. $\nabla_8 = 1-B^8$ and $\nabla = 1-B$ are seasonal and nonseasonal backward difference operators, respectively. D and d are seasonal and nonseasonal orders of differencing, respectively, selected as the minimum non-negative integers required for the data to be seasonally and nonseasonally stationary. ξ_{tm} is assumed to be a zero mean white noise process. The notation for (9) is thus $\mathrm{SARIMA}(p,d,r)\times(P,D,R)_8$. Order selection of the model for (8) is calculated by minimization of the AICc statistic (Hurvich and Tsai, 1989), which is a bias-corrected version of the AIC (Akaike, 1974). 95% confidence intervals are calculated based on the assumption that the SARIMA errors ζ_{tm} are normally distributed. The significance of the transfer function component g in (8) is tested by comparing residual sums of squares for (8) and for the corresponding SARIMA model (without the transfer function).

3. RESULTS

Catch rates taken from one of three northern zones in South Australia or additive combinations of those zones were tested in model (6) by individual fishing months or consecutive combinations of fishing months. Our best measure for a settlement index as specified in (6) is obtained by calculating central northern South Australian catch rates in May. Since May occurs near the end of the fishing season, these catch rates may be approximating unfished biomass available for spawning throughout winter and spring. In addition, it was found that the sex ratio for the May catches from 1993/94 to 1996/97 in the central northern zone of South Australia was heavily biased towards females (Prescott et al. 1998).

Lags of six and seven years were found to be the best combination for explaining annual catch variation. This result approximately agrees with Booth's (2000) New Zealand estimates which state that "most female *J. edwardsii* take 7-11 years to reach legal size, and males 5-7 years." Von Bertalanffy (1938) growth estimates were calculated for *Jasus edwardsii* near Stewart Island, New Zealand using tagged samples (McKoy 1985). According to those estimates, the minimum legal sizes of 96 mm for males and 92 mm for males would be attained at about 6 years after settlement. The minimum legal size for *Jasus edwardsii* in the Esperance area is 98.5 mm for males and females. Given that southern rock lobsters may mature approximately one year earlier in the warmer waters of the southern coast of Western Australia or the northern zone of South Australia, the six and seven year lags are in approximate agreement with these results.

q in (2) was found to be insignificantly ($p = 0.22$) different from zero. Table 1 summarises the parameter estimates for a, b, φ, q_{SA} and ω_{SA}. ω_{SA} is negative, which indicates that a stronger west-to-east current may restrict larvae from flowing against the current. The nonlinear function on the right-hand side of (6) is highly significant ($p < 0.0001$). Figure 3 depicts the relationship between annual Esperance CPUE and May catch rates lagged six and seven years from the centre of the northern zone of South Australia. (6) is fitted using the data from 1982/83 to 1998/99 (17 fishing seasons) and forecasts are made from 1999/00 to 2001/02 (Fig. 4). The forecasts reveal a large decrease in catches from a near-peak in 1999/00 to pre-1992 levels in 2001/02. Table 2 summarizes the improvement in the annual catch models.

The SARIMAX model (8) is used to predict and forecast monthly southern rock lobster catches in the Esperance area (Fig. 5). The SARIMA component that best fits the monthly catch data in (8) is $\text{SARIMA}(1,0,0)\times(1,1,1)_8$. The estimated parameters (with standard errors in parentheses) are $\hat{\phi}_1 = 0.479\,(0.080)$ for the nonseasonal autoregressive term, and $\hat{\Phi}_1 = -0.276\,(0.140)$ and $\hat{\Theta}_1 = -0.429\,(0.131)$ for the seasonal autoregressive and moving average terms, respectively. The transfer function component of this seasonal time series model is highly significant ($p < 0.0001$) with (linear) coefficient of 0.604 and asymptotic standard error 0.097. The R^2 value for SARIMAX model (8) is 85.4%, compared with 76.3% for the equivalent SARIMA model. GARCH effects appear to be marginal in the monthly time series. For example, the McLeod and Li (1983) test with $L = 24$ gives a *p*-value of 0.050. The 1999/00 to 2001/02 forecasts for monthly catches are reliable (Fig. 6) with 5 out of 24 actual data points outside the 95% confidence intervals. Model (8) has forecast a decreasing trend in annual catches from 1999/00 to 2001/02, in line with the actual fishing realizations during these three years. Catches for fishing season 2000/01 were lower than expected, similar to the annual forecasts in Fig. 4.

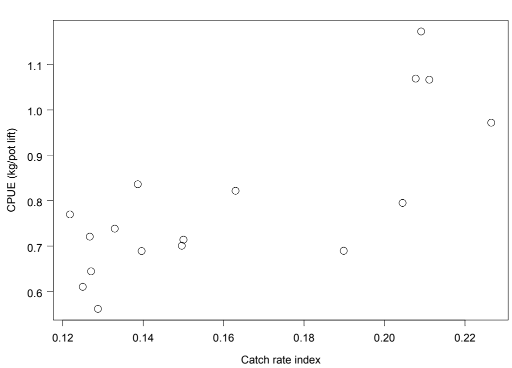

Figure 3. CPUE for the Esperance fishery from 1982/83 to 2001/02 versus catch rates from South Australia lagged six to seven years.

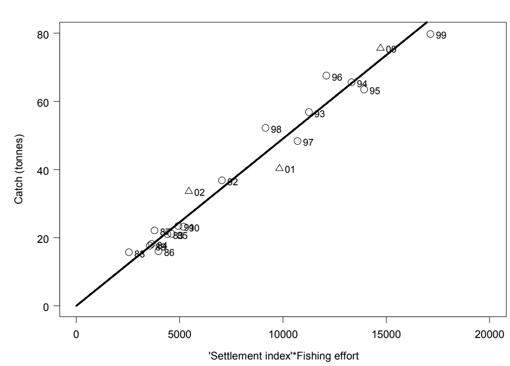

Figure 4. Annual catch-settlement index relationship for the Esperance area with forecasts from 1999/00 to 2001/02.

4. DISCUSSION

Our analysis shows that catches are correlated with relevant lagged South Australian catch rates and environmental data. Thus if South Australian catch rates for the southern rock lobster fishery in the northern zone continue to drop, it would not be surprising for the Esperance fishery to face similar difficulties. Both annual and seasonal models predicted the significant reduction in catches from 1999/00 to 2001/02. Although our models imitate a hypothesized recruitment process, there is very little biological evidence of the larval transportation phenomenon. Further investigations may be needed to show that the Jasus edwardsii fishery in Western Australia is not self-contained.

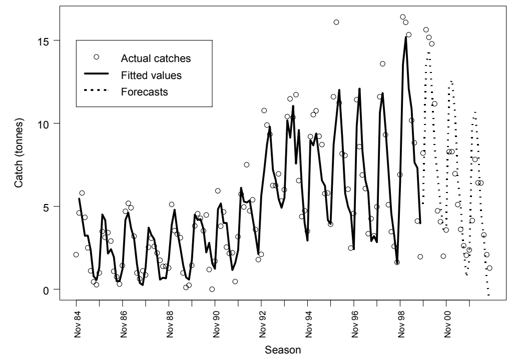

Figure 5. Predictions from 1984/85 to 1998/99 and forecasts from 1999/00 to 2001/02 by (8) of Esperance southern rock lobster monthly catches.

The Fremantle Sea Level was used to indicate the environmental factors governing the current flow. However, the effects of water currents, water temperatures and upwelling are probably more complicated in reality than the modelling of the single data stream measured at Fremantle.

The diagnostic residual time series for SARIMAX model (8) shows the presence of conditional heteroscedasticity. If the residuals are split into two subsets of equal length, namely (i) from November 1982 to February 1990 and (ii) from March 1990 to June 1997, then the ratio of the variance of series (ii) to the variance of series (i) is 4.1. Using an *F*-test, this difference is highly significant ($p < 0.0001$). The residuals plot shows that the variance undergoes a change in regime from about 1990 onwards. This timeframe coincides with the simultaneous introduction of GPS technology and live tanks to stock the lobster product. Before 1990, the lobsters were placed in freezers and stocking space was limited. From 1990 onwards, live tanks have availed more product storage space and expanded the international export market. Thus, a further model of the Esperance southern rock lobster monthly catches may include a SARIMAX model with two levels of variance. If the time series components of the model were found to involve seasonal or nonseasonal moving averages, however, the computational estimation process for this type of model would potentially be difficult.

Another problem observed during the analysis was that the assumption of normally distributed SARIMA errors resulting in the 95% confidence intervals falling in the negative catch region. A block bootstrap of the stationary, stochastic seasonal ARMA component was carried out, but there was very little improvement. A multiplicative error modelling approach is also possible as follows. Replace the additive stochastic SARIMA component on the right-hand side of (8) by a non-negative multiplicative error term from a distribution such as the lognormal density function. Then the 95% confidence intervals are theoretically and practically more valid. However, taking transformations (e.g. logarithmic) of the catch and fishing effort data may not preserve the behaviour of the autoregressive and moving average processes. Transformations may also lead to difficult estimation problems not least because there are zero catches in the southern rock lobster data.

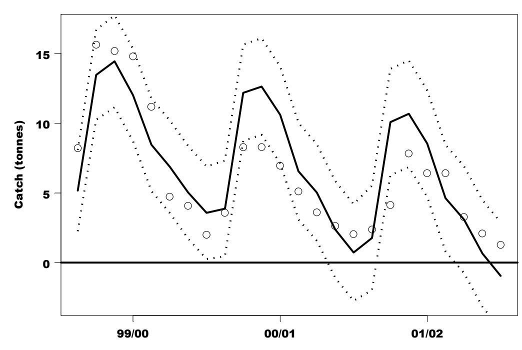

Figure 6. Forecast monthly catches (solid line) from 1999/00 to 2001/02 and 95% confidence intervals (dotted lines) assuming normal errors.

5. ACKNOWLEDGEMENTS

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Table 1. Parameter estimates with standard errors for the nonlinear regression model specified by (6).

	$\hat{a}$	$\hat{b}$	$\hat{\varphi}$	$\hat{q}_{SA}$	$\hat{\omega}_{SA}$
Estimates	4.91 (1.17)	2.94 (1.13)	0.73 (0.11)	-1.40 (0.13)	-0.070 (0.016)

Table 2. R^2 values for model subsets of (6).

	R^2	Number of parameters in model	Problems with model
Effort	87.0%	1	Time trends in residuals
Effort-recruitment	91.9%	4	1994/95 catch unexplained (< -2 std. err.)
Effort-recruitment-environment	97.0%	5	