Improving Catch Predictions for Management of the Western Rock Lobster (*Panulirus cygnus*) Fishery Using Time Series Analysis

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Abstract: The western rock lobster fishery is the most valuable single-species fishery in Australia, having posted a world record catch for rock lobster species for the 1999/00 season of 14 500 tonnes. Management is therefore interested in improving methods of catch prediction that are currently based on observed puerulus (one year-old post-larvae) settlement levels by designated collectors. The abundance of rock lobster three to four years into the future is reflected by the puerulus settlement indices for three zones, enabling accurate annual catch forecasts. However, catch forecasts for the migratory "whites" season (Nov-Jan) and the non-migratory "reds" season (Feb-Jun) are more challenging as these seasonal catches of different life history stages are significantly correlated. Thus, methods including nonlinear regression techniques and classical ARIMAX time series analysis are used to reduce the temporal bias in the seasonal catch predictions. In 1993/94, a management package was implemented to reduce the risk of exploitation in the western rock lobster fishery, to smooth the seasonal catches and to allow breeding stock levels to gradually increase. Some of the main effects of the management package on catches are analyzed in a time series intervention analysis framework. Forecasts of seasonal catches are made from 2000/01 to 2002/03 for all zones using ARIMAX time series models with puerulus settlement indices, fishing effort and management intervention terms.

Keywords: Western rock lobster; puerulus indices; nonlinear regression; time series analysis.

1. INTRODUCTION

The western rock lobster (*Panulirus cygnus*) is the most valuable single-species fishery in Australia comprising, on average, twenty percent of the total value of Australia's total fisheries production. The 1999/2000 western rock lobster catch was a world record, posting a landed catch of over 14,000 tonnes at an approximate value of A$390 million.

There are three major zones in the fishery off the Western Australian coast (Figure 1). Zone A operates between Dongara and Kalbarri, and comprises fishing grounds adjacent to the offshore Abrolhos Islands. Zone B is situated to the north of latitude 30° S, excluding that area of the fishery designated as zone A. Zone C extends south of latitude 30° S to Cape Leeuwin. The fishing season since 1977/78 consists of 7.5 months, with the migratory 'whites' fishing season operating from mid-November to January and the non-migratory 'reds' fishing season operating from February to June. These names relate to the colour of the exoskeleton of the lobsters. The lobsters moult in November and the whites moult again in February, changing colour to red. The fishing season for zone A only operates during the red season from mid-March to June. However, boats with a zone A licence are permitted to operate in zone B from November to mid-March.

To ensure that fishing pressure on this valuable fishery does not significantly reduce breeding stock levels, as occurred during the late 1980's, management can adjust fishing effort based on forecast catches if necessary [Chubb 2000]. The management objective is to keep breeding stocks at the levels of the late 1970's and early 1980's, above the biological reference point for this fishery of approximately 20-25% of the virgin biomass level [Hall and Brown 2000; Hall and Chubb

2001]. The approach to control annual catches has been possible for the western rock lobster fishery due to the relatively unique recruitment forecasting system for this stock [Caputi et al. 1995a and b].

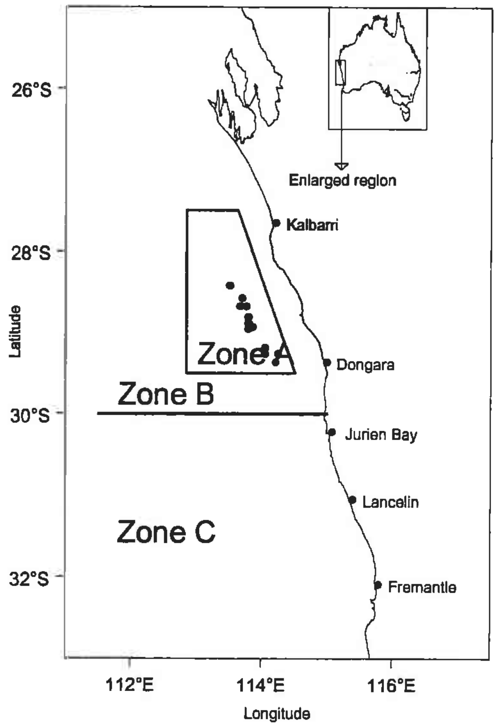


Figure 1. Map of the fishing zones off the West Australian coast for the western rock lobster industry.

During the early 1990's, it was contended that the western rock lobster breeding stock was becoming significantly reduced. Management therefore made a decision in the 1993/94 season to introduce a package aimed at a recovery in the breeding stock. The main elements of the management package that were implemented from 1993/94 to 1999/00 are as follows:

- 18% temporary reduction in pot usage;
- 1 mm increase in the legal minimum size from November 15 to January 31 ('whites' fishery);
- total protection for mature females (setose, tar-spotted and egg-bearing);
- maximum size limit for females of 115 mm for C zone and 105 mm for A and B zones).

The anticipated effects of this package included an overall reduction in exploitation rate leading to a greater survival of lobsters, a gradual boost in the number of large breeding females, a reduction of whites catches and a transfer of this reduction to the reds fishery with the objective that more lobsters are able to spawn. The 18% pot reduction is reflected through the fishing effort data. Also, a proportion of the transfer of whites catches to reds catches is due to fishing effort. However, accurate predictions of whites and reds catches and an analysis of the transfer of whites catches to reds catches requires a time series approach to account for the correlation structure of catches from one moult stage to the next and from year to year.

Seasonal catch and fishing effort data dates back to the 1964/65 season, while puerulus (post-larval) settlement information has been collected since the late 1960's at some locations. This information has been used to form a recruitment-catch relationship to predict annual catches [Caputi 1995a and b].

The focus of this paper is therefore to predict whites and reds catches for all zones of the western rock lobster fishery and to assess the effects of the 1993/94 management package on catches using time series intervention analysis and recruitment-catch relationships. Seasonal catches are forecasted from 2000/01 to 2002/03 using these classical time series models with puerulus settlement indices, fishing effort and management intervention variables.

2. METHODS

Traditionally, log-log linear regression models have been used to model catch predictions based on levels of puerulus settlement 3 to 4 years prior to the season [Phillips 1986; Caputi et al. 1995b]. Catch predictions for western rock lobster can also be made using variations of an annual puerulus-effort-catch nonlinear regression model defined by

$$C_t = a\, f\left(P_{t-3}\sin^2\theta + P_{t-4}\cos^2\theta; b\right)$$
$$E_t\left(\exp\left(-\frac{qE_t}{2} + \frac{q^2E_t^2}{24}\right)\right) + \varepsilon_{1t}, \quad (1)$$

where

$$f(x;b) = \frac{x}{bx+1} \quad (2)$$

is a Beverton-Holt [1957] mortality function, C_t is the annual catch data (kg) which can be disaggregated into whites and reds catches, E_t is the annual, whites or reds fishing effort in pot lifts, P_t is an annual accumulation of the Winsorized mean [Kendall and Stuart 1973, p.544] of puerulus settlement data obtained from up to six collectors, a, θ, b, q are parameters to be estimated and

$\varepsilon_{1t} \sim N(0,\sigma_1^2)$. The effort function in (1) is a truncation of DeLury's [1947, 1951; see Ricker 1975] abundance-effort equation.

Regarding the puerulus settlement information, there are six years of missing Abrolhos Island collector data for zone A (79/80 through 84/85). The procedure we follow is to substitute the corresponding mean-scaled Dongara puerulus settlement data from zone B, since zone A is wholly enclosed within zone B. Dongara puerulus settlement data is complete and this data set is used to model zone B catches. A similar procedure to that of zone A is used for the zone C Alkimos puerulus settlement data by replacing the indices from 69/70 to 81/82 by the corresponding mean-scaled zone C Jurien Bay puerulus settlement data. The Alkimos puerulus settlement data is regarded as more representative of the zone C catches as it is near the centre of the fishery.

When the catch series is disaggregated into white/red seasonal catches, the errors are significantly correlated for all fishing zones. Thus, a time series analysis is required for reliable predictions of white and red seasonal catches. Linear autoregressive integrated moving average (ARIMA) models [Box and Jenkins 1976] are fitted to each chronological whites/reds catch series as follows:

$$\Phi_1(B)\nabla^d\left(\frac{C_{WR,t}}{\overline{C}_{WR}}-1\right)=\Theta_1(B)\,\varepsilon_{2t}, \quad (3)$$

where $C_{WR,t}$ is the whites/reds catch series, $\overline{C}_{WR}$ is the mean of the whites/reds catches, Φ_1 and Θ_1 are finite autoregressive and moving average polynomials of orders r and z respectively, of the backward difference operator B, ∇ is a differencing operator, d is the number of differences required to achieve stationarity, and $\varepsilon_{2t} \sim N(0,\sigma_2^2)$.

The order component (r,d,z) of the ARIMA model for each zone is selected by minimization of Akaike's [1974] bias-corrected AICc statistic [Hurvich and Tsai 1989]. To validate the stationarity and invertibility conditions and to avoid nonlinear time series likelihood calculations, we estimate $\{\theta,b,q\}$ in (1) sub-optimally by performing a nonlinear regression and then enter the deterministic component of (1) as a transfer function component of an ARIMA transfer function (ARIMAX) model. White and red seasons are fitted separately for the nonlinear regression model (1) to estimate $\{\theta,b,q\}$ for each season.

Two dummy intervention variables that measure a mean increase in catches or a further transfer from whites catches to reds catches that is not reflected through fishing effort as an effect of the 1993/94 management package are also analyzed as transfer function components. The whites (reds) seasonal intervention variable is defined as 1 for the whites (reds) season from 1993/94 onwards, and 0 otherwise.

The ARIMAX model is therefore defined as follows:

$$\Phi_2(B)\nabla^d\left(\frac{C_{WR,t}}{\overline{C}_{WR}}\right)=\Phi_2(B)\nabla^d\left(\sum_{i=1}^{N_T}\alpha_i\frac{T_{i,t}}{\overline{C}_{WR}}\right)+\Theta_2(B)\varepsilon_{3t}, \quad (4)$$

where N_T is the number of transfer function variables, $T_{i,t}$ $(i=1,\ldots,N_T)$ comprise the transfer function variables, α_i $(i=1,\ldots,N_T)$ are the transfer function coefficients needed to be estimated, Φ_2 and Θ_2 are autoregressive and moving average polynomials of orders r and z, respectively, as in (3) and $\varepsilon_{3t} \sim N(0,\sigma_3^2)$ is assumed. Asymptotic F tests are conducted on the transfer function variables to attain their significance for each zone.

3. RESULTS

Table 1 summarizes the parameter estimates and R^2 values for parsimonious models of the form (1) that describe whites and reds catches for respective zones. For all models, estimates for the nonlinear parameter $\hat{q}$ were insignificant. The inclusion of fishing effort enhances all zone B and C models, however fishing effort is not included in the zone A model. The puerulus settlement indices are significant for prediction of catches for zones B and C, but only significant for the zone A model when a dummy intervention variable (taking 0 values before 1993/94 and 1 values from 1993/94 onwards) is included.

Tables 2 and 3 describe the ARIMA and ARIMAX model fits and estimated parameters for the annual (reds) catches for zone A and the whites/reds chronological catch series for zones B and C. There are significant autocorrelations in catches taken from all zones from one moult season to the next and from year to year (Table 2). The puerulus settlement indices, combined with fishing effort in the case of zones B and C, obtained from nonlinear regression models (1) remain significant variables in these time series models.

The intervention variables represent percentage increases or decreases in whites and reds catches from 1993/94 onwards. These terms are significant for all zones, however the two intervention terms for zone C could be replaced by a single one, expressed as the sum of the two terms, since there is no significant difference between these. This means there is no significant transfer from whites to reds catches other than that which is reflected through fishing effort for zone C. Estimates from (1) and the intervention terms are therefore included as transfer functions in the ARIMAX models for all zones. Using these exogenous variables, seasonal ARIMAX catch predictions are shown for each zone in Figure 2, and forecasts for the three seasons 2000/01 to 2002/03 are calculated.

Table 1. Parameter estimates (and standard errors) and R^2 values for catch-puerulus-effort nonlinear regression models given by (1).

	$\hat{a}$ $(\times 10^5)$	$\hat{\theta}$	$\hat{b}$	R^2
Zone A	2.990 (1.829)	0.438 (0.570)	0.163 (0.108)	13.3%
Zone B : whites	1.014 (0.264)	0.912 (0.155)	0.042 (0.014)	67.3%
Zone B : reds	0.911 (0.267)	0.692 (0.178)	0.041 (0.015)	78.8%
Zone C : whites	9.342 (2.753)	1.122 (0.157)	0.254 (0.093)	62.0%
Zone C : reds	6.412 (1.325)	0.839 (0.121)	0.172 (0.047)	59.2%

The ARIMAX models are validated by fitting the catch data up to 1996/97 and comparing the forecast catches (with 95% confidence intervals) between 1997/98 and 1999/00 with the actual catches. For all zones, actual catches are within the forecasted confidence intervals for the three years.

Assessing the fishing effort effects of the 1993/94 management package, the changes in fishing effort in pot lifts are calculated by comparing 6-year means in effort immediately before and after the reduction in effort in 1993/94 for zone C and 1992/93 for zone B. The results are that fishing effort decreased by 18.6% in zone A, 24.2% and 18.4% for the white seasons in zones B and C, respectively, and 8.6% and 10.4% for the red seasons in zones B and C, respectively. The parsimonious ARIMAX model for zone A does not involve fishing effort and there is no whites season for zone A, so no changes would be expected from the pot reduction and minimum size change since 1993/94. However, setose females may affect the catches in zone A. In fact, the significant positive intervention term in the zone A ARIMAX model indicates overall catches have increased by 8.1% since 1993/94 despite the 18.6% decrease in fishing effort and the greater protection of females. There is evidence that some of the transfer from whites catches to reds catches for zones B and C is reflected by fishing effort since the percentage decreases in fishing effort for zone

Table 2. ARIMA and ARIMAX models and R^2 values for whites/reds chronological catch series for each zone.

	ARIMA		Puerulus index + Fishing effort ARIMAX	
	Model (r,d,z)	R^2	Model (r,d,z)	R^2
Zone A:				
without intervention	(0,0,1)	38.3%	(0,0,1)	48.7%
including intervention	(0,0,1)	43.1%	(0,0,1)	56.7%
Zone B:				
without intervention	(2,0,2)	72.7%	(1,0,2)	83.3%
including intervention	(2,0,1)	73.0%	(1,0,2)	88.7%
Zone C:				
without intervention	(3,0,0)	63.7%	(0,0,2)	70.5%
including intervention	(3,0,0)	66.6%	(2,0,1)	80.6%

Table 3. Estimated ARIMAX model (4) coefficients (with standard errors) for whites/reds catches.

	Puerulus index + effort on whites catches	Puerulus index + effort on reds catches	Whites inter-vention	Reds inter-vention
Zone A Puerulus index		0.9952 (0.0208)		
Puerulus index + intervention		0.9738 (0.0207)		0.0813 (0.0375)
Zone B Puerulus index	0.9901 (0.0325)	1.004 (0.0341)		
Puerulus index + intervention	1.0147 (0.0253)	0.9308 (0.0275)	-0.0583 (0.0489)	0.2446 (0.0508)
Zone C Puerulus index	0.9979 (0.0314)	0.9925 (0.0330)		
Puerulus index + intervention	0.9491 (0.0318)	0.9121 (0.0348)	0.1464 (0.0611)	0.2300 (0.0671)

B during the white seasons exceeded 18% and the fishing effort for zones B and C during the red seasons decreased by significantly less than 18%. This reflects the latent fishing capacity which existed in the reds fishery. For zone B, the intervention analysis indicates significant decreases (-0.0583, Table 3) in whites catches transferring to increases in reds (0.2446, Table 3) catches beyond that which was reflected through fishing effort. For zone C, however, a further transfer (0.1464 and 0.2300, Table 3) from whites to reds catches since 1993/94 appears insignificant.

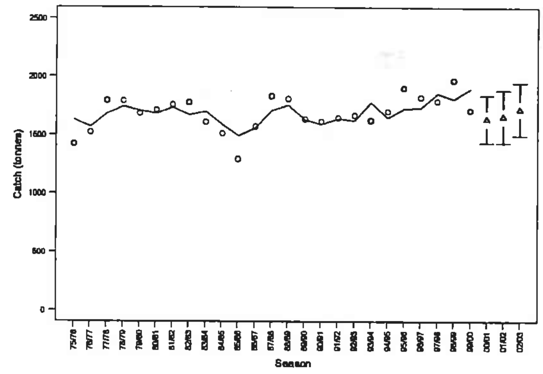
4. DISCUSSION

The seasonal catch predictions and thus forecasts are significantly enhanced by the usage of ARIMAX time series models. These models account for significant correlations in the catch data while fitting the puerulus settlement indices and fishing effort information together with intervention variables associated with some of the outcomes of the 1993/94 management package. The time series models focus more accurately on the annual catches for zone A and the proportions of whites and reds catches for zones B and C. Seasonal catches were forecasted for the three years from 2000/01 to 2002/03 using the most parsimonious time series models encountered in this analysis.

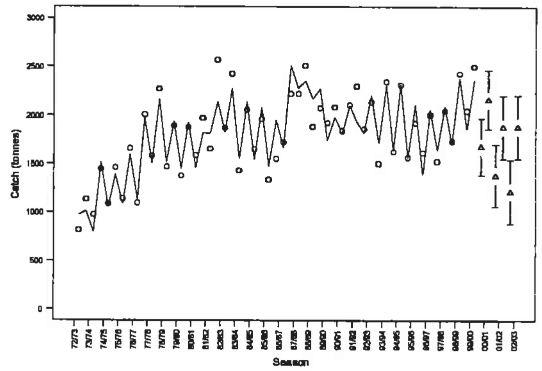
The 1993/94 management intervention process has been effective in zones B and C. In particular, there have been significant transfers from whites to reds catches in zones B and C. For zone C, this was due to effort. For zone B, however, the intervention variables detected a further transfer from whites to reds. This reflects a higher proportion of smaller lobsters (76 mm) in zone B compared to zone C. Our methods used dummy variables that described instantaneous changes in catches and then constant effects of intervention for all years. These assumptions may not be valid. Mixture distribution time series methods may more accurately model the gradual and long-term effects of the management intervention process.

Further research is required to optimally estimate the nonlinear transfer function parameters for the ARIMAX equations presented in this paper. Our approach was hierarchical whereby nonlinear regression estimation was used and the estimated parameters were then put into the time series models. The effects are minimal for the modelling procedures in this paper, but errors would increase for a hierarchical monthly time series analysis.

Zone A



Zone B



Zone C

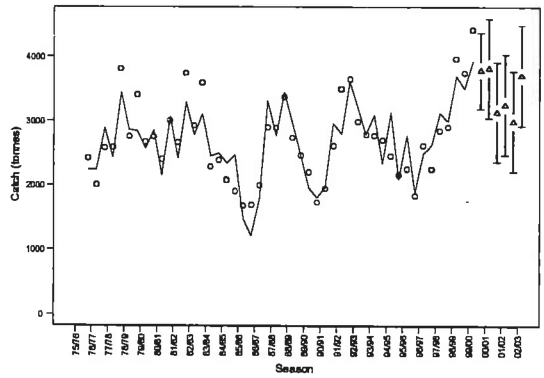


Figure 2. ARIMAX time series catch predictions and forecasts (2000/01 to 2002/03) with 95% confidence intervals for zones A, B and C, respectively.

5. ACKNOWLEDGEMENTS

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