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ABSTRACT

Catch and effort data 1977-1994 were used to develop a model to estimate quotas and effort controls for the Turks and Caicos Islands conch fishery. Two biomass dynamic models are proposed, one with a constant rate of increase and a second with the rate of increase proportional to an external index. The models were fitted to the catch-effort time series without assuming equilibrium. Uncertainty in the choice of model and the parameter variances suggest that: (1) fishing controls will require careful monitoring and frequent adjustment, (2) effort controls were more robust than catch quotas, (3) future research should be directed at measurable factors influencing the population's rate of increase, such as the spawning stock size.

Although conch is an important resource for many countries in the Caribbean region (Appeldoorn and Rodriguez, 1994), few stock assessments have included population dynamics. To date, studies are limited to assessments of conch density (Friedlander et al., 1994; Glazer and Berg, 1994). This is largely due to the lack of time series data on population size or catches in many fisheries. In contrast, the Turks and Caicos Islands has an extensive catch-effort time series currently extending from 1977 to 1994. This study uses these data to examine the response of the conch population to fishing and assess how the population has changed over time.

Olsen (1985) fitted the Schaefer (1954) model to catch-effort data from the Turks and Caicos Islands (Berg and Olsen, 1989). As well as estimating maximum sustainable yield (MSY) and fishing effort to attain MSY, their analysis suggested that the stock was being overfished at the time of their publication. This study had two problems: (1) the method used to fit the model assumed the stock was at equilibrium, and (2) the data they used contained many errors. In this study we extend the assessment used by Olsen (1985) in three ways. Most importantly, we avoided the equilibrium assumption. This is much more realistic, and should provide better estimates of parameters. We also compiled the catch-effort data used in the study from original daily records. This removes many significant recording errors from the analysis. Finally we consider a extension of the original model which allows for variable recruitment.

THE FISHERY

The Turks and Caicos Islands are located at the south-eastern end of the Bahamas and consist of three shallow water banks separated by channels with depths in excess of 1000 m. The largest of these, the Caicos Bank, supports a significant fishery for lobster (Panulirus argus (Latreille)) and conch (Strombus gigas), the combination of shallow sand substrate and small patch reefs forming an ideal habitat for these two species.

Lobster is the preferred catch, because lobster landings prices exceed conch by a factor of four. Fishermen switch to conch during the closed season for lobster or when conch catch rates are particularly high. Due to the similarity in fishing methods, fishermen who dive can switch easily between the two fisheries. Before 1966 conch was the dominant export as a dried product. However with freezing technology introduced in 1966 conch was replaced by lobster as the main fisheries product, so that conch landings declined to a very low level by 1970. Catches in the last two decades show two peaks, around 1977-1980 and 1984-1987 (Fig. 1). These peaks partly reflect the status of the lobster fishery. With declining lobster catch rates, fishermen have tended to switch to conch, and with very poor catch rates leave the fishery altogether for alternative employment.

Fishermen generally leave the dock around 07:00 and return by 16:00. The length of a fishing day is variable and will depend, among other things, on weather conditions. Each boat usually carries a boat driver and 1-2 divers. Most boats are now made of fibreglass and have 55-70 hp outboard engines. Conch are collected by free diving (only mask, fins and snorkel) in waters usually less than 10m deep. Although conch aggregations can be found down to 20 m, fishermen generally do not work in depths greater than 10 m because the weight of the shells make it difficult to bring several conch at a time to the surface,

The boat driver removes the conch shells while the divers are collecting, so this processing has little effect on the catch rate. Search time dominates a conch fishing day, so that catch-per-unit-effort (CPUE), measured as kg boat-day^{-1}, is likely to be inversely related to conch density, and therefore proportional to the stock size. Catches of conch are recorded as pounds of meat landed at the end of each fishing day in one of the fish processing plants. There are currently five fully operational plants. Conch are removed from their shells at sea, landed and processed to leave only the white muscle, which is frozen for export.

Effort is measured in boat days. Catch data is available for the period 1966-1995 and effort data for the period 1977-1995, with the exception of years 1984-1985 when effort was not recorded by the Fisheries Department.

POPULATION MODELS

The Turks and Caicos Islands data set consists only of landings in weight and effort, making biomass dynamic models the most appropriate. The simplest of these models (Schaefer, 1954) provides a simple and robust description of population changes where the population size is limited by a carrying capacity of the environment.

$$B_{t+1} = B_t - C_t + rB_t(1 - B_t / K)$$

where B_t = biomass at time t, C_t = catch during time t, r = intrinsic rate of increase, and K = carrying capacity.

The model parameters (i.e., the carrying capacity K and the rate of increase r) are likely to vary over time. The carrying capacity of the Caicos Bank may depend upon a fluctuating conch food source. However, the conch population, depleted by fishing, may exhibit a reduced dependence on food source fluctuation, so that K has little apparent variation. The largest source of variation might therefore be the rate of increase r. The rate of increase could include variations in the growth rate (indicating food availability) as well as new recruits. The main sources of variability are physical environmental effects, such as weather or temperature, and changes in biological factors, including changes in size frequency and the relative numbers of spawning individuals.

Although it may be recognized that parameters can vary, understanding and estimating that change without more detailed information is usually impossible. However in this case we were able to propose an alternative population model which made use of a recruitment index developed for the spiny lobster Panulirus argus (Medley and Ninnes, unpubl. data). The index is based on the abundance of new recruits to the lobster fishery, which was estimated for the seasons 1977-1995 using a simple constant recruitment depletion model (Allen, 1966) of the catch and effort data at the start of the lobster fishing season. This recruitment index is used in place of r in the model (Eq. 1).

$B_{t+1} = B_t - C_t + \lambda I_t B_t(1 - B_t / K)$

where I_t = recruitment index at time t, and λ = recruitment factor converting the index to an intrinsic rate of increase.

There are two reasons that a lobster recruitment index might index conch recruitment as well. First, both species share similar habitat during their initial life stages. Physical and biological factors could affect both these species during pelagic and early post-settlement life in the same way. Second, since 1977 lobster and conch have been subject to the same depletion and subsequent recovery. Fishing could affect size structure of the populations of both species in a similar way, resulting in decreased recruitment, a factor which it is thought to have contributed to fluctuations in lobster landings (Medley and Ninnes, unpubl. data). Therefore both lobster and conch recruitment could be dependent on the same third variable, past fishing effort.

Maximizing economic yield may be more important than maximizing catch. As fishing increases on a previously lightly exploited stock, the stock size will decrease and assuming the catch rate is proportional to the stock size, the costs for landing a unit weight of fish will increase. Price, cost and discount rates can be added to the Schaefer model to derive optimal equilibrium catch (C_{opt}) and effort (f_{opt}) quotas (Clark, 1990). However they must only be used for guidance since, in contrast to the fitting method, they assume the population will remain at equilibrium through appliance of the control.

$B^* = K / 4[(c / pqK + 1 - \delta / r) + \sqrt[2]{(c / pqK + 1 - \delta / r)^2 + 8c\delta / pqKr}]$

$C_{opt} = rB^*(1 - B^* / K)$

$f_{opt} = r / q(1 - B^* / K)$

where B^* = optimal population size (biomass), q = catchability, p = price per unit biomass landed, c = cost per unit effort and δ = discount rate. Prices and costs are used from 1992, when cost data was available. The average cost of 1 d of fishing was $112 per boat excluding labor, and the average landed price $0.62 per pound. The discount rate measures the way future economic returns are valued, and is similar to bank interest rates. With a zero discount rate, Equation 3 will maximize the catch value minus the catching costs in each year, often known as the maximum economic yield (MEY). As the discount rate increases, the value of future returns diminish, leading to increased fishing pressure to realize earlier higher catches.

FITTING METHOD

The population models (Eqs. 1, 2) used all available catch data 1966-1994 in their calculation, but were only fitted to those years where effort had been recorded (1977-1983, 1986-1994). The 1995 season data were used to compare the CPUE predicted by the models with the observed CPUE.

The method used to fit the models does not assume the fishery is at equilibrium (i.e., that catch equals biomass production), but fits the difference equations as dynamic models to the catch and effort time series (Hilborn and Walters, 1992). Each year's stock biomass is calculated as the previous year's stock biomass plus the stock growth minus the catch (Eqs. 1, 2). Given the start biomass (in this case the unexploited biomass, K), model parameters (r, K) and the catch time series, the time series of stock size can be calculated. The expected catch can be calculated using each season's fishing effort, a catchability parameter, and the stock size.

$E(x_t) = \mu_t = qf_tB_t$

where μ_t = expected catch in year t, f_t = observed fishing effort, q = catchability and B_t = stock biomass defined by the constant-r (Eq. 1) or variable-r (Eq. 2) population models. Fitting the dynamic model to data involves minimizing a measure of the difference between the observed and expected catch time series.

The models were fitted to the data using weighted least-squares, which finds the parameter values minimizing the weighted squared difference between the observed catches and expected catches generated by the model.

minimise D = [Graphic Character Omitted] $w_t(x_t - \mu_t)^2$

where μ_t = expected catch in year t (Eq. 4), w_t = data point weight, x_t = observed catch. The weights account for changes of variance. Examination of the residuals suggests their variance changes over the length of the time series, with 1977-1983 showing greater variability than the 1986-1994 period (Fig. 2) These two halves of the time series were each given an inverse-variance weighting to account for this change. The weights were calculated as the reciprocal of the variance of the monthly within-year CPUE. There is no explanation for the change in variance, which could be related to changes in fishing activities, environmental variability or the way data were recorded.

There is no analytical solution to find the minimum (Eq. 5), and so it is necessary to use numerical routines. Such routines are widely available in commercial packages such as spreadsheets. There are also available dedicated catch-effort data analysis packages such as CEDA (ODA, 1992) which will fit a number of alternative population models and provide parameter confidence intervals.

RESULTS

The constant-r model provides a reasonable fit to the data (r^2 = 0.900, 16 df; Fig. 2), but possesses two problems. Firstly, the observed CPUE 1977-1983 tends to lie consistently below the expected CPUE. Secondly, the model largely fails to predict the continued high catch rates in 1995. The parameter estimates suggest the unexploited stock size (K) is relatively small, but the large intrinsic rate of increase (r) indicates the stock is capable of rapid recovery (Table 1). Historically the model suggest that although catches in the short term were often above the sustainable yield, the stock size was not depleted to a point beyond MSY.

The variable-r model provides a better fit to the data (r^2 = 0.932, 16 df) than the constant-r model, also demonstrated by the narrower parameter confidence intervals (Table 1). The model explains the observed CPUE 1977-1983 well and does a little better in predicting the 1995 catch rate (Fig. 2). The better fit of this model suggests that the rate of increase may be variable and that the high stock size 1992-1994 may be partly attributable to the higher r than average for the period 1977-1994. This model also places a different interpretation on past catch and effort data, suggesting the stock was depleted beyond MSY by 1987 (i.e., $B_t < K/2$), as a result of low biomass growth during this period (Fig. 3).

Maximum economic yield will be reached before MSY, and therefore MSY is unlikely to be the preferred economic target unless the discount rate is very high (Fig. 4). The infinite discount rate is equivalent to the open-access situation, where all economic rent is dissipated. At this point they would be making no profit on a trip, so fishermen would not willingly fish beyond an infinite discount rate level unless subsidized. In reality opportunity costs are greater than zero assumed here, as it is likely they would have a better alternative livelihood well before this point is reached. At the other extreme the 0% discount rate maximizes the profit each year (MEY), but treats future revenue the same as present revenues. A more realistic discount rate would be 10%, which encourages higher fishing effort than MEY, but less than MSY.

Economic results suggest the optimum effort lies between 3500 and 4500 boat days and optimum catch between 650,000 and 750,000 kg (Fig. 4). The standard errors for these estimates also suggest that effort controls are more robust than catch quotas. With effort quotas, landings will automatically adjust to the true population size allowing for a greater degree of error in population size estimates.

CONCLUSIONS

The implication of the analysis is that any steady state control is dangerous, and requires careful monitoring. This is particularly true if depletion of the stock decreases the rate of increase, r. Without an explicit connection between stock size and r, the mean quota and effort controls for the variable-r model (Table 1) will over-estimate the optimum catch or effort. In the light of this, conservative quotas based on the constant-r model may well be the best choice until more information becomes available, although frequent adjustment would still be required to ensure overfishing did not occur (Fig. 3). Unfortunately a conservative quota would result in significant losses in good seasons if effort is kept too low and would become very difficult to enforce. Fishermen would be fully aware of the abundance of conch, and would rightly object to a control which unnecessarily prevented them from fishing.

Ideally it would be possible to track r and ultimately predict changes. Accurate prediction of r would allow quotas to be set each year in line with expected stock production. Assuming the index captures true variability in r, adopting a fixed management control on fishing could lead to 30% less catch than could be achieved if accurate predictions of the r parameter were available for each year (Table I). In its current form the variable-r model is not appropriate to predict stock production. Although a recruitment index of another species explains previous fluctuations in conch production, it would be foolish to use this for prediction without a firm understanding of why such a correlation exists. A more direct measure of r is required. With the degree of uncertainty in conch population dynamics, the constant-r model still provides the basis for sound management advice.

It is particularly important to identify whether fishing affects r to ensure this factor is taken fully into account in management controls. Of the variables which may be related to the rate of increase, the priority would be to assess population characteristics of the stock which can be affected by fishing, such as the age or size structure. Since conch are landed without their shell, measurements will have to be based on soft tissue. There is no known way to age conch from soft tissue, however weight and sexual maturity can be measured with comparative ease. It may be possible to find a link between the ratio of sexually mature animals to the rate of increase.

Effort controls rather than catch quotas significantly reduce uncertainty for management as well as directly addressing economic concerns. Effort controls exhibit both lower confidence intervals, and smaller differences between the models (Fig. 4). However quotas possess the significant advantage that they are easily enforced where the majority of the catch is exported. For the Turks and Caicos Islands, a flexible annual quota system, tempered by current catch rates and estimates of the population size, is probably the best current option.

ADDED MATERIAL

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Table 1. Parameter estimates with 95% confidence intervals for the Schaefer model. Maximum sustainable yield (MSY), effort at MSY (f_{MSY}) and CPUE at MSY ($CPUE_{MSY}$) are calculated from the other parameters. The r parameter in the variable-r model is the fitted parameter multiplied by the average recruitment index. MSY, f_{MSY} and $CPUE_{MSY}$ for the variable-r model are the mean for the series 1977-1994 (Fig. 3).

Model	Parameter	Estimate	95% Confidence intervals	
Constant-r				
	K (kg)	4846270	3954812	6235834
	r ($year^{-1}$)	0.57	0.45	0.72
	q (boat day^{-1})	$6.44\ 10^{-05}$	$4.17\ 10^{-05}$	$8.37\ 10^{-05}$
	MSY (kg)	687338	668064	727906
	f_{MSY} (boat-days $year^{-1}$)	4401	3907	5662
	$CPUE_{MSY}$ (kg boat-day^{-1})	156	124	169
Variable-r				
	K (kg)	4433858	3955807	5245846
	r ($year^{01}$)	0.70	0.57	0.81
	q (boat day^{-1})	5.90E-05	$5.12\ 10^{-05}$	$6.58\ 10^{-05}$
	MSY (kg)	781393	740926	810576
	f_{MSY} (boat days $year^{-1}$)	5968	5157	6507
	$CPUE_{MSY}$ (kg boat-day^{-1})	131	125	143

Figure 1. Conch landings from 1966 to 1995. Catches before 1977 are based on unverified landings records.

Figure 2. Observed (*) and expected catch per boat day (CPUE) for the constant-r (-) and variable-r (—) models. The models were used to predict the 95 season CPUE (+).

Figure 3. Maximum biomass production (i.e., MSY) estimated for the constant-r (-) and variable-r (—) models. To stabilize the stock size in the variable-r model a quota would have to track the fluctuating biomass production. The variable-r model suggests the low production 1985-1987 coupled with high catches (Fig. 1) led to overfishing.

Figure 4. Optimal catch and effort quotas with 95% confidence intervals based on the constant-r ([Graphic Character Omitted]) and variable-r ([Graphic Character Omitted]) model estimates, which maximize the discounted economic rent from the fishery. The 0 discount rate indicates the maximum economic yield (MEY) and infinite discount rate, the fishery under open access.

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