Evaluating closed season options with simulation for a tropical shrimp fishery

Reg A. Watson and Victor R. Restrepo

We used simulation modelling to find seasonal closures which maximized either yield per recruit (Y/R) or relative value per recruit (V/R) for several tropical shrimp fisheries. Each case examined represented a choice of (1) a single versus a multicohort population, (2) the reduction of annual fishing effort levels through closures versus its redistribution to the fishing season, and (3) a range of fishing mortality levels. Under most conditions, seasonal closures which maximized Y/R also maximized V/R, though simulated gains in the latter were smaller. Timing of seasonal closures was more critical for fisheries of single-cohort populations than multicohort populations. Multi-cohort-based fisheries required shorter seasonal closures to maximize V/R than did those based on single-cohort populations. Assumptions about the disposition of fishing effort normally expended during the period of a seasonal closure greatly affected the best closure choice. Predicted best closures were of a longer duration when annual fishing effort was simply redistributed rather than reduced by closures. Greatest improvements in Y/R (30 to 40%) were obtained for fisheries based on single-cohort populations when closure effort was redistributed. Predicted increases in Y/R for multicohort-based fisheries never exceeded 7%. The duration of best closures increased with increasing values of fishing mortality when the annual fishing effort was reduced by closures. This trend was reversed when annual fishing effort was conserved. As fishing mortality increased, potential gains in Y/R or V/R improved at the cost of equilibrium egg production.

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Introduction

Seasonal closures have been used to control fishing effort and/or to prevent growth overfishing in many tropical and subtropical shrimp fisheries. Closures have been used in Australia (Grey and Buckworth, 1983; Somers, 1985), the USA (Leary, 1985), Nicaragua (Lightburn-Moses, 1985), Kuwait (Morgan, 1984), and elsewhere. Shrimps are fast-growing, short-lived, and highly valued. To maximize catch value per recruit, the timing of the harvests may be critical. If fished too soon, shrimp are under-sized and of little commercial value; if fished too late, gains in value due to growth are offset by losses due to natural mortality. Thus the timing of a desirable closure is influenced by characteristics of the species' life history, such as the timing of recruitment, growth rate, and natural mortality rate.

The Torres Strait shrimp fishery in northern Australia has been managed with seasonal closures since 1985 (Watson and Mellors, 1990). Managers who set the timing of these closures have assumed a need to protect a single recruitment pulse from growth overfishing. In addition, they usually assume that closures reduce total annual fishing intensity. New evidence, however, indicates that the major commercial species of shrimp in the fishery (*Penaeus esculentus* Haswell, 1879) recruits into the fishery year-round (Blyth *et al.*, 1990). In addition, annual fishing is not always reduced with closures, even though the fishing season is shortened. Anticipation of valuable catches immediately following closures can encourage fishing and actually increase annual fishing effort (Nichols, 1982).

In this study we examine how assumptions about the frequency of recruitment (single versus multiple pulses),
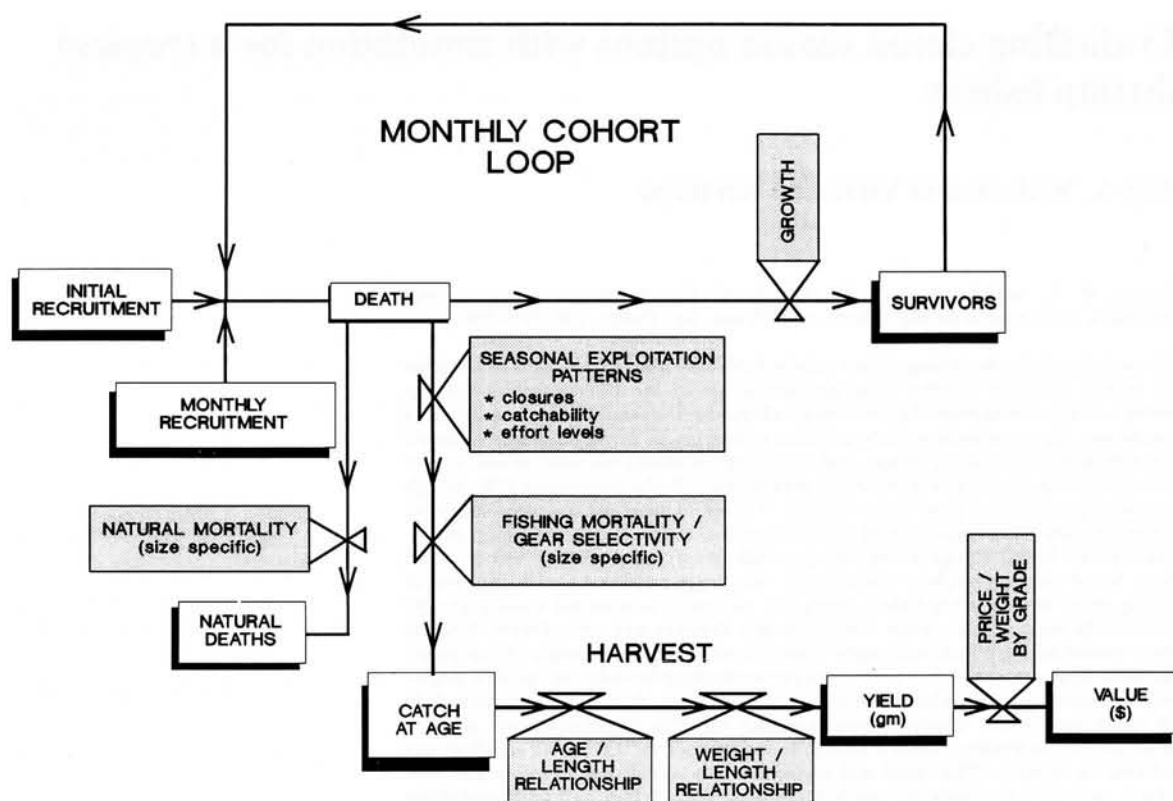
Figure 1. Schematic representation of the simulation model showing processes involved.

and the level and monthly pattern of fishing effort can affect decisions regarding the timing of seasonal closures and their potential benefits.

Methods

Simulation model and fixed parameter values

The simulation program used incorporates traditional mathematical relationships employed to model fish population dynamics. The main difference between this and other generalized simulators (e.g. Fox, 1973) is that some dimensions and processes are tailored to fit tropical shrimp-like life cycles. The model is structured to make monthly computations of growth, mortality, and reproductive values for up to 12 monthly cohorts of shrimp and assumes that each cohort lives up to one year (Fig. 1). Each simulation modelled the fishery under a fixed set of conditions for a period of two years so that equilibrium values could be calculated. In what follows, we present the basic relationships used and the parameter values set for every experiment.

The tropical shrimp fisheries we simulated were loosely based on the fishery for *Penaeus esculentus* in

Torres Strait, northern Australia. Though survey data provided estimates of some biological parameters such as growth rates, others such as natural mortality rates were estimated from the literature (García, 1985) and therefore our results were intended mostly for illustrative purposes.

Let i (i = 1,2...12) denote the month (age in months), and j (j = 1,2...12) be the cohort number. Mortality is represented by an exponential decline, such that:

$$N_{i+1,j} = N_{i,j}\exp(-Z_{i,j}), \tag{1}$$

where N denotes the population numbers at the beginning of the month, and Z is the instantaneous coefficient of total mortality, given by:

$$Z_{i,j} = M_{i,j} + y_{i,j}f_i. \tag{2}$$

Here $y_{i,j}$ is the selectivity of cohort j in month i (defined by Equation (3) below) and f_i is the fishing effort expended in month i. The instantaneous coefficient of natural mortality, M, is age-cohort specific and dependent on length using an array of values for various size ranges (Table 1).

The instantaneous coefficient of fishing mortality on

Table 1. Monthly instantaneous coefficients of natural mortality, M, grouped for ranges of carapace lengths (mm) (developed from García, 1985).

Carapace length	M
0–9	0.3
10–14	0.25
15–44	0.2
45+	0.3

cohort j in month i, $F_{i,j}$, is represented by the second term on the right side of Equation (2). The monthly fishing efforts used are given in Table 2 and the values of size(age)-dependent selection, $y_{i,j}$ were computed from:

$$y_{i,j} = \frac{1}{1 + \exp[x_2(\bar{L}_{i,j} - x_3)]}, \qquad (3)$$

where $y_{i,j}$ is the proportion of fully selected animals of cohort j in month i of mean length $\bar{L}_{i,j}$, $x_2 = -0.396$ and $x_3 = 20.4$. Fishing mortalities referred to in the text corresponded to fully selected ages.

Growth follows a von Bertalanffy equation and the average monthly carapace lengths for each cohort are approximated by the values predicted in the middle of each month. Growth parameters were estimated by tag-return experiments. Length–weight conversions were obtained with a simple power function with parameters estimated from laboratory measurements. The growth and length–weight conversion parameter values used in the simulations are given in Table 3. Using the computed lengths and weights of the catch, monthly yield is given by

$$Y_{i,j} = C_{i,j}\bar{W}_{i,j}, \qquad (4)$$

where $C_{i,j}$ is the monthly catch of cohort j in month i (defined in Equation (6) below) and $\bar{W}_{i,j}$ is the mean weight of cohort j in month i.

Average monthly population sizes are given by:

$$\bar{N}_{i,j} = N_{i,j}(1 - \exp(-Z_{i,j}))/Z_{i,j}, \qquad (5)$$

and each cohort's monthly catch is given by:

$$C_{i,j} = F_{i,j}\bar{N}_{i,j}. \qquad (6)$$

For computing the value of the catch, the model uses an array of relative values (expressed as a proportion of the maximum ex vessel price obtained by a survey of local shrimp buyers) for ranges of carapace lengths (Table 4).

The simulation also computes egg production, E, with the relationship:

$$\bar{E}_{i,j} = P_{i,j}\bar{N}_{i,j(\text{Females})}Q_{i,j}, \qquad (7)$$

where:

Table 2. Proportionate monthly fishing effort values (without F-multiplier applied) used in the simulations. Values are for closures beginning 1 January. Closure periods appear shaded.

Fishing effort Disposition	Closure Length	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Redistributed	0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	1	0.0	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	2	0.0	0.0	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	3	0.0	0.0	0.0	0.3	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	4	0.0	0.0	0.0	0.0	0.3	0.3	0.1	0.1	0.1	0.1	0.1	0.1
	5	0.0	0.0	0.0	0.0	0.0	0.4	0.3	0.1	0.1	0.1	0.1	0.1
	6	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.3	0.2	0.1	0.1	0.1
	7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.3	0.3	0.1	0.1
	8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.4	0.3	0.1
	9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.4	0.3
	10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.5
	11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2
Reduced	0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	1	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	2	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	3	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	4	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	5	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	6	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1
	7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1
	8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1
	9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1
	10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
	11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1

Table 3. Parameters for the von Bertalanffy growth equation (from tag-return experiments) and the weight (g) to carapace length (mm) relationship (from laboratory measurements) for male and female *Penaeus esculentus*.

	Growth function		Weight–length	
	k	L_∞	a	b
Male	0.17	37	0.0024	2.72
Female	0.27	42	0.0026	2.67

Table 4. Relative shrimp ex vessel prices (maximum scaled to 1.0) grouped for ranges of carapace lengths (mm) (obtained from telephone survey of Cairns, Queensland shrimp buyers, 1990).

Carapace length	Relative value
0–20	0.0
21–24	0.31
25–29	0.56
30–38	0.82
38+	1.0

Table 5. Monthly recruitment numbers and proportions of mature females (after parameter C in Restrepo and Watson, 1991) assumed gravid (G in Equation (8)) used for simulations of single and multicohort populations.

	Recruits		Proportion of mature females (G)	
Month	Single cohort	Multicohort	Single cohort	Multicohort
Jan	0	411 794	0	0.569 26
Feb	0	205 901	0	0.463 03
Mar	0	441 209	0	0.402 57
Apr	0	735 294	0	0.404 08
May	0	588 235	0	0.467 17
Jun	0	382 307	0	0.574 92
Jul	0	161 799	0	0.698 42
Aug	0	132 300	0	0.804 58
Sep	0	152 900	0	0.864 91
Oct	0	500 000	0	0.863 24
Nov	0	735 294	0.6337	0.800 45
Dec	453 919	1 000 000	0	0.692 78

$$P_{i,j} = \frac{G_i}{1 + \exp(a - b\bar{L}_{i,j})} \quad (8)$$

is the proportion of mature females of size $\bar{L}_{i,j}$ that produce eggs in month i, and G, a and b are parameters (a = 14.62, b = 0.464 and monthly values of G^i appear in Table 5, and were modelled after Restrepo and Watson (1991));

$$Q_{i,j} = h + m\bar{L}_{i,j} \quad (9)$$

is the average fecundity of individual females (h = −536 291 and m = 22 573 after Crocos (1987)).

Equilibrium values of yield, value, and egg production are computed by summing the variable of interest for all cohorts throughout their lifetimes. For instance, yield per recruit is computed as

$$Y/R = \sum_{i=1}^{12} \sum_{j=1}^{12} Y_{i,j} \Big/ \sum_{i=1}^{12} N_{i,j}. \quad (10)$$

Experimental design

Our main objective was to find the combination of closure starting data and duration that would maximize yield per recruit (Y/R) or relative value per recruit (V/R), which we will refer to as the best closure, for the different cases outlined below. We limited the number of closures in a calender year to one. For each case we recorded yield, catch, value, biomass, and egg production, which enabled evaluation of different closure options. The variables that define our different case studies are described below.

Single vs. multicohort

All simulations below assumed a fishery based on either a single cohort or a 12-cohort population (multicohort). The monthly recruitment and egg production potentials used for these two cases appear in Table 5.

Closure starting date and duration

We simulated seasonal closures by reducing fishing mortality for the months involved to zero. In all cases, all possible combinations of closure starting months, January through to December, were tried with every possible closure length (one to 11-month closure).

Closure effort reduced vs. redistributed

The fishing effort that would have been expended during any of the above closures could, in one extreme, be simply redistributed to other non-closure months, particularly to those immediately following the closure period. Alternatively, this effort could be lost completely and annual fishing mortality reduced in proportion to the length of the closure. Both of these cases were simulated with all closure combinations. Fishing effort schedules used in the simulations appear in Table 2. In addition to these schedules we used fishing mortality multipliers (F-multipliers) to vary the overall magnitude of fishing mortality. Three F-multipliers (0.5, 1 and 5) were used. Resultant annual fishing mortality levels were calculated as the sum of all the monthly fishing mortality values for the year (from Equation (3) and Table 2) × the F-multiplier.

In total, 1,596 combinations were simulated (two populations × two effects of closure on effort × three F-

Table 6. Best seasonal closures predicted from simulations. The shaded bars represent the seasonal closures which maximized either (a) yield per recruit or (b) value per recruit for each of the cases examined. Cases considered the response of total annual effort to closures (redistributed versus reduced) and the number of cohorts in the population (one versus 12). Included are percentage changes resulting from closures in either yield per recruit or relative value per recruit, biomass, and egg production compared to virgin stocks.

Disposition of closure effort	No. of cohorts	F multiplier	Annual F	Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec	% Change resulting	% Virgin biomass	% Virgin eggs
(a) Yield/Recruit							
Redistributed	Single	1	1.2	▓▓▓▓▓▓	41.4	63.5	30.2
	Multiple		1.2	▓▓▓▓▓▓	6.8	75.1	62.1
	Single	5	6.0	▓▓▓▓▓▓	30.2	43.6	0.3
	Multiple		6.0	▓▓	4.1	32.1	9.7
Reduced	Single	1	1.0	▓ ▓	0.3	71.4	43.1
	Multiple		1.2		0.0	71.1	58.0
	Single	5	4.0	▓ ▓	14.2	43.2	2.4
	Multiple		5.0	▓ ▓	2.1	34.9	12.7
(b) Value/Recruit							
Redistributed	Single	1	1.2	▓▓▓▓▓▓	41.3	63.5	30.2
	Multiple		1.2	▓▓▓▓▓	3.0	70.1	55.6
	Single	5	6.0	▓▓▓▓▓	22.8	32.0	0.3
	Multiple		6.0	▓	2.5	32.1	9.7
Reduced	Single	1	1.0	▓ ▓	0.6	71.4	43.1
	Multiple		1.2		0.0	71.1	58.0
	Single	5	4.0	▓ ▓	9.7	43.2	2.4
	Multiple		5.0	▓ ▓	0.8	34.9	12.7

multipliers × 12 starting months × closure durations, in addition to the 12 combinations possible without a closure which we included for comparison). For one specific case, that of a 2-month closure, we varied the F-multiplier from 1 to 10 in 18 steps so that the response surface for Y/R could be presented clearly.

Results

Single vs multicohort

The timing of seasonal closures which maximized Y/R or V/R differed between simulations of fisheries based on single and multicohort populations. Generally, the best closures for the multicohort-based fishery were shorter in duration, and the potential increase in Y/R or V/R was much smaller than for their single-cohort counterparts (Table 6). Increases of 30 to 40% in Y/R were predicted for fisheries of single-cohort populations if effort was redistributed. In contrast, increases in Y/R for a multicohort fishery under the same conditions were less than 7%. Simulations with high F levels (4 to 6) resulted in severely reduced egg production (0 to 13% of virgin levels) whether a seasonal closure was used or not.

Simulations of a two-month seasonal closure for a single-cohort based fishery provided clear information about the best starting date. This is illustrated in Figures 2a and 2c by the peaks in Y/R at high F levels when the closure started in the second month. In contrast, choices were not so clear for the multicohort-based fishery, which had flatter response surfaces (Figs. 2b and 2d). Whether the annual fishing effort was redistributed or reduced due to the closure had comparatively little effect in this example likely because the proportion of annual fishing effort expended during a two-month closure is relatively small.

Closure effort reduced vs. redistributed

The closures which maximized Y/R or V/R in cases where effort was reduced differed from those where effort was redistributed (Table 6).

When effort was reduced the predicted best closures were comparatively short, which resulted in higher annual F values. At higher F-multiplier values the best closures were longer. Predicted gains in Y/R or V/R were often negligible and in one case (multicohort, F-multiplier = 1) the best results were obtained without a closure (Table 6). In contrast, when effort was redistributed after the fishery reopened, then the predicted best closures were lengthy (up to 11 months in some cases, Table 6). Potential gains in Y/R or V/R were high for the
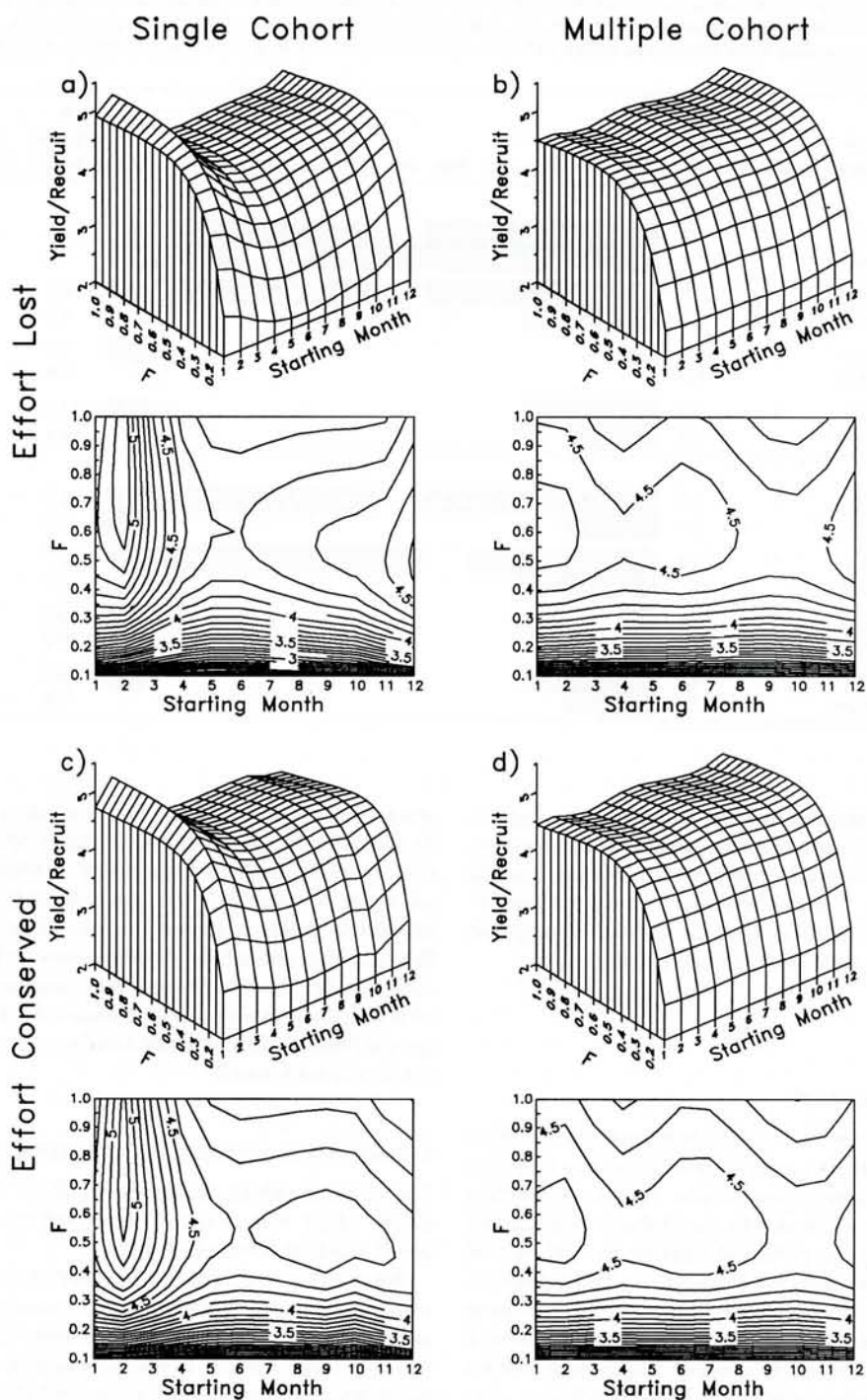
Figure 2. Surface and contour plots of yield per recruit predicted for a two-month closure starting in any of 12 months (1 = January) using a range of F-multipliers. Assumptions were: (a) single cohort population, closure reduced annual fishing effort; (b) multicohort population, annual fishing effort reduced; (c) single cohort population, annual fishing effort redistributed; and (d) multicohort population, annual fishing effort redistributed.

single cohort fishery but smaller for the multicohort case.

Yield vs. value per recruit

Generally, seasonal closures which maximized Y/R also maximized V/R (Table 6). When effort was redistributed, however, seasonal closures which maximized V/R were much shorter than those which maximized Y/R for a multicohort-based fishery. Usually potential gains in V/R through seasonal closures were smaller or similar to increases in Y/R.

Discussion

In this study we have shown how assumptions about the nature of recruitment (single vs. multiple pulses) can affect the specifications of ideal closures. As expected, when the fishery operates on a single-cohort rather than multicohort population, the timing and duration of a closure that maximizes Y/R can be identified more clearly. Models of shrimp fisheries typically assume that these fisheries exploit essentially single-cohort stocks (Dudley and Waugh, 1980; Penn and Caputi, 1985). Though this may be realistic for some fisheries, it is incorrect for many populations that are known to spawn throughout the year (García, 1985; Blyth *et al.*, 1990). Our study indicates that if a multicohort population is wrongly assumed to be a single-cohort one then the benefits predicted from using a particular closure can be misleading. Often, the results would exaggerate predicted gains in Y/R.

The effect of closures on annual fishing mortality also affects such choices. It is often assumed that seasonal closures result in reduced annual fishing effort. Evidence from the Gulf of Mexico (Nichols, 1982) and northern Australia (Watson, unpubl.) suggests that this is not always the case. Increases in annual fishing effort can result from fishermen's anticipation of particularly good harvests when the season opens, or because the closure enables them to be well prepared to exert maximum fishing pressure, or both. As this study has shown, this could greatly lengthen the duration of closures which maximize Y/R. Thus, perceptions about the disposition of fishing effort that would be expended without a closure can produce greatly differing results. Our simulations focused on only two extreme possibilities. In one case, annual fishing decreased in direct proportion to the length of the closure; in the other case, fishing mortality remained constant on an annual basis, regardless of the closure length. The latter case represents an unrealistic situation for very long closures (e.g. $F \geqslant 1.0$ for an 11-month closure). A more likely situation for most fisheries probably lies somewhere between the two extremes we examined.

There are obvious costs to fishing, both fixed and effort-related, which should be weighed when the financial advantages of seasonal closures are considered. Short closures have been used to advantage in northern Australia, allowing fishermen to schedule vessel refits, survey inspections, gear repair, and annual holidays without any competitive disadvantage.

One factor which we did not examine, and which mitigates against lengthy seasonal closures, is their effect on product prices, particularly when fishing resumes. Conroy and Poffenberger (1986) examined the effects of the Gulf of Mexico Texas shrimp closure on shrimp prices and values. They concluded that losses due to reductions in product prices caused by oversupply were small compared to potential gains due to increases in the average value of shrimp through growth.

Closed seasons have been used in the Gulf of Carpentaria, northern Australia to protect spawners. This has potential merit if peaks of egg production exists, and if fishing can disrupt the mating or spawning processes. Several commercial shrimp species in northern Australia, including *Penaeus esculentus* (Keating *et al.*, 1990) and *Penaeus longistylus* (Courtney and Dredge, 1988), have peaks of spawning activity, but a detrimental effect of fishing on egg production has not been established.

By allowing for a unilateral cessation of fishing, seasonal closures could have social benefits. They can reduce the risk of overexploitation of common property resources which many otherwise be under threat. Dudley and Waugh (1980) found that shrimp closures in South Australia reconciled both private and social objectives regardless of the degree of capitalization and were therefore a "socially optimal" method of resource management. When social factors were quantified and included in a model along with biological and economic factors, conclusions about the merits of closed seasons are a little less clear. Krauthamer *et al.* (1987) found that under a closed-inshore policy the inshore landings of the Texas shrimp fishery decreased, resulting in a 92% decrease in rent to the inshore fishery. With their model they followed the performance of individual inshore vessel classes and concluded that changes in policy, such as seasonal closures, have different economic impacts on different groups of fishermen, particularly the lowest producers.

We found that an important decision in the use of simulation for tropical shrimp fisheries is how to realistically model responses in the level and pattern of fishing effort to changes in the duration of closures. Effective marine fisheries management requires an understanding not only of biology and of resource species population dynamics, but also of the economic relationships within fisheries and sociological factors that affect decisions

made by individual fishermen (Krauthamer *et al.*, 1987). Management regulations such as seasonal closures affect fishermen in complex ways, their responses affect fleet dynamics and hence fishing mortality. These human responses can largely determine whether such management measures are successful or not.

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