North American Journal of Fisheries Management 13:326–336, 1993

Closed Seasons and Tropical Penaeid Fisheries: A Simulation Including Fleet Dynamics and Uncertainty

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Abstract.—Seasonal fishery closures are commonly used in fisheries management for various purposes, including limitation of effort, protection of spawners, and maximization of the yield or value that can be obtained from a cohort. The effectiveness of a proposed closure can be evaluated through yield-per-recruit analysis, which can be carried out analytically for some simple situations. For other fisheries, such as the penaeid shrimp fishery of Torres Strait, Australia, investigated here, the analyses are more complex because recruitment occurs in pulses throughout the year and the intensity of fishing is itself unevenly distributed in time, being patterned after these recruitment pulses. Furthermore, the imposition of closures of different durations has been documented to alter the pattern and intensity of fishing after the fishery reopens. In this study, a simulation approach is used to identify the timing and duration of closures that are likely to increase the yield or the value per recruit of the fishery. The simulation allows for changes in the distribution and magnitude of effort directly caused by the closures. All input parameters are assumed to be known precisely, except those controlling fishing and natural mortality, which are drawn from empirically derived ranges. The simulation results indicate that a 6-month closure starting in December or January could increase the value of the fishery by 5–10%, compared with a fishery with the same fishing pattern and no closure.

The temporary or seasonal closure of a fishery is a management tool often used to reduce fishing effort and to limit harvests. It may also modify the temporal pattern of fishing effort and prevent growth overfishing of fast-growing species. Fishery closure is employed for both purposes in tropical and subtropical shrimp fisheries in Australia (Somers 1985), the USA (Leary 1985; Nance et al. 1988), Nicaragua (Lightburn-Moses 1985), Kuwait (Morgan 1984), and elsewhere.

Tropical shrimp are fast-growing, short-lived crustacea with a high commercial value that increases with the weight of animal. The timing of harvests may be critical to maximize catch value per recruit. Shrimp fished too soon are undersized, of little commercial value, and often discarded by the fishing fleet. If shrimp are fished too late then gains in value due to growth may be offset by losses due to natural mortality. A seasonal closure will prevent growth overfishing only if seasonal patterns of fishing mortality can be adjusted to prevent exploitation of undersized animals. Whether this adjustment is possible or not depends on characteristics of the species' life history (seasonal recruitment patterns, growth rates, and natural mortality rates) and on the effects of seasonal closure on the pattern of fishing effort.

Many authors have investigated methods of optimizing the use of a single regulation, such as a catch quota (Moussalli and Hilborn 1986), an effort control (Hannesson 1987), or a gear restriction, or a combination of regulations (Dudley and Waugh 1980; Stollery 1984) for fisheries management. Methods developed for evaluating fishery closure regulations are, however, less common and seldom address the issue of closure optimization. Certain fishery closures act effectively as minimum-size regulations, and yield per recruit (Beverton and Holt 1957) may be used as an analytical method for their evaluation. If, however, the effect of the closure cannot be equated to a minimum-size regulation then a more complex dynamic model is required for assessment. Such a model may need to incorporate the relationships between closure length, closure timing, stock dynamics, and fleet dynamics. Because of the complexity of these relationships this type of model generally does not have an analytical solution and has to be implemented as a computer simulation (Watson and Restrepo, in press).

Stock assessment methods rarely incorporate detailed modeling of the interaction between population and fleet dynamics. There is, however, evidence that this interaction is critical to the success of a regulation imposed into a fishery (Hilborn 1985). Modeling fleet behavior is not easy since there are many factors (economic, social, and operational) that determine the reaction of fishing boats to different fishery conditions. Nevertheless, simple models of fleet behavior (Clark 1985; Hilborn 1985; Allen and McGlade 1986) may greatly enhance our ability to understand the reactions of a fishery system to different regulations.

A deterministic computer simulation model based on a utility-per-recruit formulation (Die et al. 1988) is used to investigate alternative closure regimes defined by the length and the timing of the fishery closure. The model incorporates relevant aspects of fleet dynamics and parameter uncertainty to provide managers with risk-oriented advice about the effects of seasonal closures on yield, value, and eggs per recruit.

Methods

Simulation Model

Traditional yield-per-recruit models assume that recruitment takes place during a brief time in the year. Under such circumstances, the potential gains in weight or value per recruit that can be made by imposition of a closed fishing season are very sensitive to the timing and duration of the closure. For tropical penaeid shrimp and other crustacea that reproduce throughout the year, it may be highly unrealistic to assume a single recruitment pulse. More realistic per-recruit analyses can be conducted with an approach such as that of Watson and Restrepo (in press), which relaxes the single recruitment pulse assumption by allowing up to twelve monthly cohorts to be recruited during the year. The equation symbols are defined in Table 1, and the equations used in the model are given in Table 2. The subscript i denotes month of the year and j denotes cohort membership (j = 1–12 for January–December cohorts).

In their model, Watson and Restrepo (in press) assumed fishing effort was constant throughout the year, and that in the event of a closure, total annual fishing effort would be either maintained or reduced proportionally to the closure length. Herein Watson and Restrepo's (in press) model was modified (Figure 1) to incorporate more realistic scenarios about the effects of seasonal closures on fishing effort patterns, as described below.

TABLE 1.—Definition of symbols used in simulation model. The subscripts i and j denote month of the year and cohort membership, respectively.

$A_{i,j}$ = price (Australian \$/kg)
$B_{i,j}$ = value of catch (Australian \$/kg)
$C_{i,j}$ = catch (numbers)
d = proportion of fishing effort redistributed from the closed to the open season
E/R = eggs per recruit
$E_{i,j}$ = egg production
$F_{i,j}$ = instantaneous fishing mortality rate (monthly)
F_{mult} = fishing mortality multiplier
f_i = fishing effort (h)
f_i' = fishing effort adjusted for seasonal closure (h)
$f_{\max}$ = maximum value of f_i
f_r = fishing effort normally put into the closed season (h)
g = binomial parameter for the redistribution of fishing effort function
H_i = parameter in proportion mature at length relationship
h = number of months since opening of fishing season
k = growth coefficient of Von Bertalanffy growth equation
$L_{i,j}$ = carapace length (mm)
L_{50} = length at 50% selection (mm)
L_{∞} = asymptotic length of Von Bertalanffy growth equation (mm)
$M_{i,j}$ = instantaneous natural mortality rate (monthly)
M_{mult} = natural mortality multiplier
$N_{i,j}$ = population size at the beginning of the month
$\bar{N}_{i,j}$ = average population size
$P_{i,j}$ = proportion mature females
q = catchability
r = fleet saturation parameter
$S_{i,j}$ = selectivity
t = age of fish (month)
t_0 = age at zero length in Von Bertalanffy growth equation (month)
u = length of fishing season (month)
V/R = value per recruit
$V_{i,j}$ = fecundity
$W_{i,j}$ = weight (g)
x_i = proportion of annual recruitment
Y/R = equilibrium yield per recruit
$Y_{i,j}$ = yield (g)
$Z_{i,j}$ = instantaneous coefficient of total mortality (monthly)
α = parameter of length–weight relationship
β = parameter of length–weight relationship
γ = parameter in natural mortality–length relationship (annual)
δ = parameter in natural mortality–length relationship (annual)
λ = parameter in proportion mature at length relationship
ρ = parameter in proportion mature at length relationship
σ = slope of selectivity curve
ϕ = parameter in fecundity at length relationship
ω = parameter in fecundity at length relationship

First, the present, model acknowledges the presence of a seasonal pattern of fishing effort, f_i (i.e., effort in month i), that is related to the seasonal pattern of shrimp recruitment to the fishing grounds. Second, it assumes fishing effort pulses

TABLE 2.—Summary of per recruit simulation model (modified from Watson and Restrepo, in press). Symbols are described in Table 1.

Parameter	Equation
Population size	$N_{i+1,j} = N_{i,j}e^{-Z_{i,j}}$
Monthly instantaneous mortality rates	$Z_{i,j} = M_{i,j} + F_{i,j}$
	$F_{i,j} = qS_{i,j}f_i$
	$M_{i,j} = \frac{\gamma e^{-\delta L_{i,j}}}{12}$
Selectivity	$S_{i,j} = \frac{1}{1 + e[-\sigma(L_{i,j} - L_{50})]}$
Growth	$L_{i,j} = L_\infty[1 - e^{-k(t-t_0)}]$
	$W_{i,j} = \alpha L_{i,j}^{\beta}$
	$Y_{i,j} = C_{i,j}W_{i,j}$
Average monthly population size	$\bar{N}_{i,j} = N_{i,j}(1 - e^{-Z_{i,j}})/Z_{i,j}$
Catch	$C_{i,j} = F_{i,j}\bar{N}_{i,j}$
Value of monthly catch	$B_{i,j} = C_{i,j}W_{i,j}A_{i,j}$
Monthly egg production	$E_{i,j} = P_{i,j}N_{i,j(\text{females})}V_{i,j}$
Proportion mature	$P_{i,j} = \frac{H_i}{1 + e^{\lambda-\nu L_{i,j}}}$
Fecundity	$V_{i,j} = -\omega + \phi L_{i,j}$
Equilibrium yield per recruit	$Y/R = \sum_{i=1}^{12}\sum_{j=1}^{12} Y_{i,j} \Big/ \sum_{i=1}^{12} N_{i,j}$

are generated at the onset of the fishing season as a reaction to seasonal closures. Fishing effort pulses are modeled by assuming that a certain portion, d, of the effort normally put in the closed season, f_r, is redistributed to the open season;

$$f_r = \begin{cases} \sum_{i=i_1}^{i_2} f_i & \text{if } i_1 \leq i_2 \\ \sum_{i=i_1}^{12} f_i + \sum_{i=1}^{i_2} f_i & \text{if } i_1 > i_2; \end{cases} \tag{1}$$

i_1 and i_2 are the first and last month of the closure respectively (January implies $i = 1$; December implies $i = 12$).

The redistributed effort is assigned to the open season months according to a binomial distribution defined by the number of open months, u, and by a binomial parameter, g. The amount of fishing effort in each of the open months f_i is then calculated as,

$$f_i' = f_i + f_r d\binom{u}{h}g^h(1 - g)^{u-h}; \tag{2}$$

h represents the number of months since the fishing season opened and is calculated as

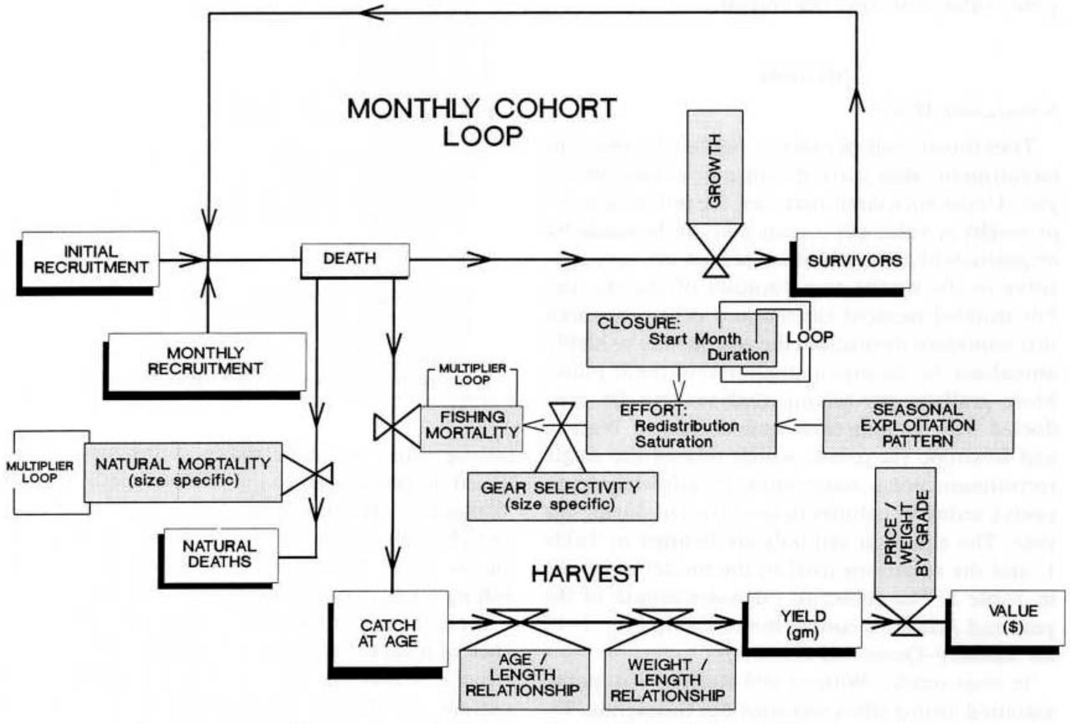

FIGURE 1.—Visual representation of simulation model.

TABLE 3.—Values of parameters used in the simulation model: (a) monthly specific, (b) sex specific, (c) size specific, (d) fixed, and (e) associated with uncertainty. Monthly specific parameters: i = calendar month; f_i = fishing effort in 10^3 h; x_i = proportion of annual recruitment; and H_i = asymptote of the proportion of mature females. Other symbols are defined in Table 1.

(a) Monthly specific parameters

Month i	f_i	x_i	H_i
1	0.97	0.08	0.80
2	3.08	0.04	0.70
3	4.50	0.08	0.57
4	2.64	0.14	0.46
5	3.05	0.11	0.40
6	2.30	0.07	0.40
7	2.44	0.03	0.46
8	2.43	0.02	0.57
9	2.47	0.03	0.70
10	1.55	0.09	0.80
11	0.86	0.13	0.86
12	0.23	0.18	0.86

(b) Sex-specific growth parameters

Sex	L_∞ mm	k_{month}	t_0	α	β
Females	42.0	0.27	0.0	0.0026	2.67
Males	37.0	0.17	0.0	0.0024	2.72

(c) Size-specific parameters

$L_{i,j}$ (mm)	<9	9–19	19–24	24–26	26–36	>36
$A_{i,j}$ (Australian $/kg)	0.0	1.7	5.0	7.0	9.7	15.2

(d) Fixed parameters

q	σ	L_{50}	γ	δ	λ	ρ	ω	ϕ
$9 \cdot 10^{-5}$	0.3	21.5	5.51	0.027	14.7	0.46	$5 \cdot 10^6$	$2 \cdot 10^5$

(e) Parameters associated with uncertainty

$M_{\text{mult}} = 0.75, 0.8, 0.85, 0.9, 0.95, 1, 1.05, 1.1, 1.15, 1.2, 1.25$

$F_{\text{mult}} = 0.75, 0.8, 0.85, 0.9, 0.95, 1, 1.05, 1.1, 1.15, 1.2, 1.25$

$d = 0.5$

$r = 2, 4, 6$

$$h = \begin{cases} i - i_2 & \text{if } i > i_2 \\ i - i_2 + 12 & \text{if } i \le i_2. \end{cases} \tag{3}$$

To model the pulse of effort at the onset of the fishing season the parameter g was adjusted so that 50% of the redistributed effort would always be put in the first month of the open season:

$$\binom{u}{1} g(1 - g^u) = 0.5. \tag{4}$$

Third, the model incorporates a saturation parameter, r, that controls the maximum amount of fishing effort which could be exerted by the fleet in any month:

$$f_i' = \begin{cases} f_i' & \text{if } r \cdot f_{\max} > f_i' \\ r \cdot f_{\max} & \text{if } r \cdot f_{\max} \le f_i'; \end{cases} \tag{5}$$

$f_{\max}$ is the monthly fishing effort at the peak of the fishing season (the maximum value of the f_i vector).

A final difference with respect to Watson and Restrepo's (in press) model is that the present model allows for uncertainty in the parameters that define fishing and natural mortality, as discussed in the section below.

Model Parameters

The model parameter used loosely represented those of the trawl fishery for tiger prawn *Penaeus esculentus* in Torres Strait, northern Australia (Table 3). As in most tropical fisheries, knowledge of population and fishery parameters is limited, and in many cases there is no information at all. Survey data provided estimates of sex ratio, reproductive activity, and growth rates for both sexes (Keating et al. 1990). Data on abundance of juvenile shrimps (Blyth et al. 1990) were used to estimate relative monthly recruitment factors, x_i, and logbook data were used to estimate fishing effort patterns (Watson et al. 1990b).

For simplicity, it was assumed that recruitment, growth, and reproductive parameters were known without error. Other parameters, such as fishing and natural mortality rates, the amount of effort redistributed due to the closure, and the level of fishing effort saturation, were drawn from empirically derived ranges and therefore subject to much more uncertainty. Some of the choices for these parameter values are ad hoc and are included here mainly for illustrative purposes. In order to incorporate the uncertainty associated with these parameters, the simulations were carried out with a large number of combinations of mortality values (Table 3, subhead e). Our approach was to carry out the computations with 11, evenly distributed, *M* (natural mortality rate) and *F* (fishing mortality rate) values from what were considered to be reasonable ranges for these parameters. In addition, three values were used for the parameter that controls the amount of effort that is redistributed after a closure (*d*), and three for the parameter that controls fishing fleet saturation (*r*). Thus, in each simulation of a closure of a given length and duration, 1,089 runs were made with all the combinations of *F, M, r*, and *d*.

For each run, the results (yield, eggs, or value per recruit) were compared against a run with the same mortality parameter values and no seasonal closure. The results, expressed as percent change, were averaged to give the expected relative change in yield or value for a given closure. In addition, the proportion of runs giving a positive change in yield or value were computed.

Results

Fleet Dynamics

Given the number of factors controlling fishing effort (and corresponding mortality) patterns in the model it is important to describe in detail the behavior of the simulated fleet. There were four parameters (closure length, closure start, proportion of redistributed effort, and effort saturation) that determined the changes which occurred in the seasonal pattern of effort as a result of the imposition of a seasonal closure. The effect of each parameter can be investigated by changing one and holding all the others constant. First, as closure length increased, the pulse of fishing mortality at the onset of the fishing season increased in intensity (Figure 2a). Second, shifts in the start of the fishing season also affected the intensity of the mortality pulse; stronger pulses occurred when the closed season was associated with those months that normally support intensive fishing (Figure 2b). Third, the higher the proportion of effort redistributed to the open season, the stronger the intensity of the mortality pulse (Figure 2c). Finally, fleet saturation limited the intensity of the pulse in cases where unrealistically high pulses would have been predicted by the model (Figure 2d).

Changes in the seasonal fishing pattern due to fishery closures resulted in changes in the annual fishing mortality exerted by the fleet. The simulations used values of *d* (the proportion of effort redistributed) of 0.5, 1.0, and 1.5; over all parameter combinations this parameter has no effect on the annual fishing mortality. In contrast, the values (2, 4, 6) used for *r* (the saturation parameter) reduced the annual fishing mortality because extreme pulses of effort were eroded by the effects of saturation. Thus long closures were associated with lower annual fishing mortality than were short closures (Figure 3). Different closure starts were also associated with different annual fishing mortality values because the intensity of effort pulses differed depending on the timing of the closure. Differences in annual fishing mortality due to closure timing are smaller, however, than those associated with closure length (Figure 3).

Yield per Recruit

On average there was a reduction in yield per recruit (*Y/R*) with seasonal closures compared with an open fishery (Figure 4a). Most closures were comparatively neutral in their overall effect, especially those of shorter duration that started midway through the year. The percentage of runs for all mortality combinations that yielded a positive effect on *Y/R* was also highest (>60%) for midyear closures lasting less than 6 months as well as short closures starting at the beginning or end of the calendar year (Figure 4d).

Value per Recruit

Closures beginning at the start of the calendar year and lasting slightly more than one half of the year had the effect of increasing value per recruit (*V/R*) by more than 10% over that of an open fishery (Figure 4b). This improvement was also observed with shorter closures starting midyear. Many other closure combinations had little effect on *V/R*. Closures that gave the greatest average increases also gave improvements in *V/R* in more than 75% of the cases (Figure 4e).

Eggs per Recruit

All egg-per-recruit (*E/R*) values obtained in the presence of closures were compared to that of a permanently closed fishery (virgin stock). As expected with the introduction of fishing, in all closure combinations there was a reduction in egg production. All closures with a duration shorter than 6 months reduced *E/R* by about 50–65% whereas longer closures reduced *E/R* between 30 and 50% (Figure 4c).

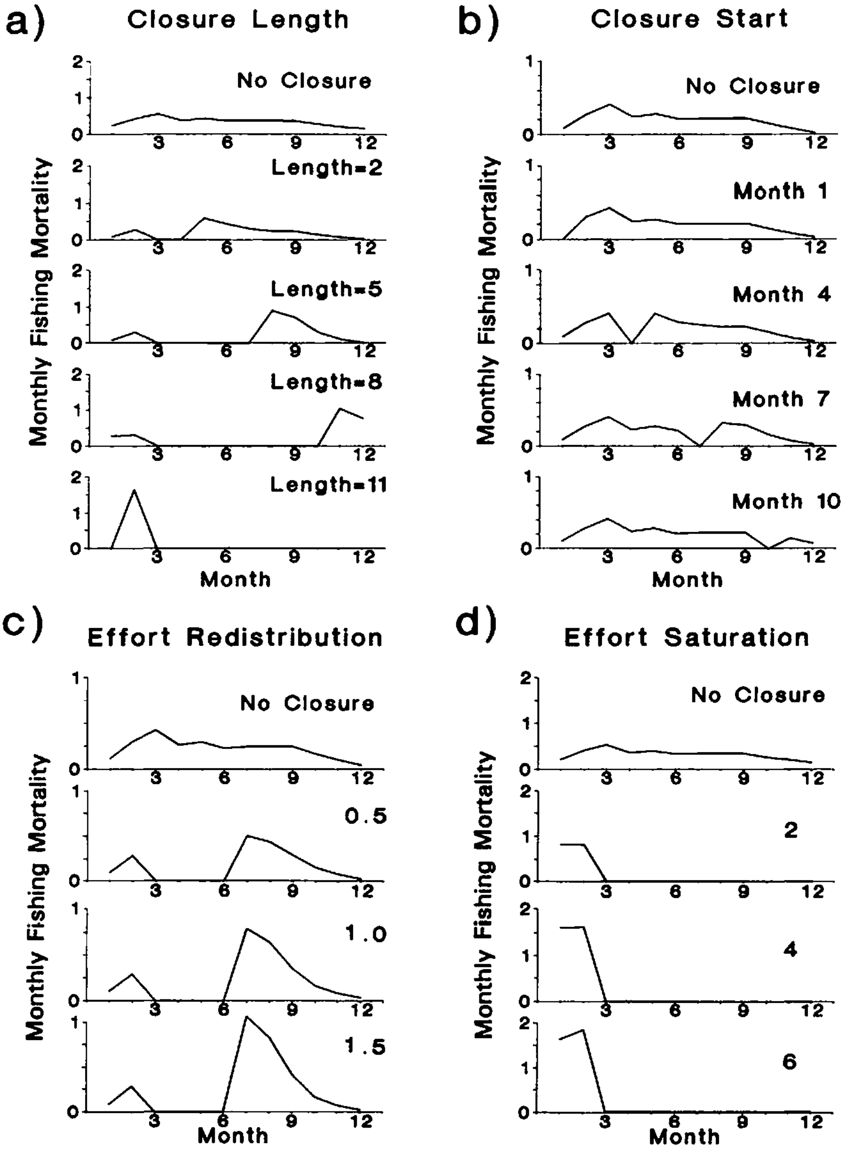

FIGURE 2.—Effects of altering (a) closure length (months), (b) closure start (month), (c) effort redistribution parameter, *d*, and (d) effort saturation parameter, *r*, on the seasonal fishing mortality pattern of a simulated tiger prawn fishery in Torres Strait, northern Australia.

Sensitivity

Predictions from the model were comparatively insensitive to changes in the fleet saturation parameter. With a 50% reduction in *r* there was a 3.5% reduction in both *Y/R* and *V/R* but a 5% increase in *E/R* (Figure 5a). A 50% increase in *r* caused only about a 1% increase in *Y/R* and *V/R* and resulted in a 1% decrease in *E/R*.

The model outputs were more sensitive to changes in the effort distribution parameter. A 50% reduction in *d* resulted in a decrease in *Y/R* and *V/R* of about 10% and an increase in *E/R* of about 12% (Figure 5b). An increase of 50% in *d* increased *Y/R* and *V/R* by 4% and decreased *E/R* by 6%.

A fishing mortality multiplier, F_{mult}, was used to scale age- and cohort-dependent fishing mortality rates (Table 3). Reducing F_{mult} by 25% reduced *Y/R* and *V/R* by 10% and increased *E/R* by 14% (Figure 5c). Increasing F_{mult} by 25% increased *Y/R* and *M/R* by 7% and decreased *E/R* by 12%.

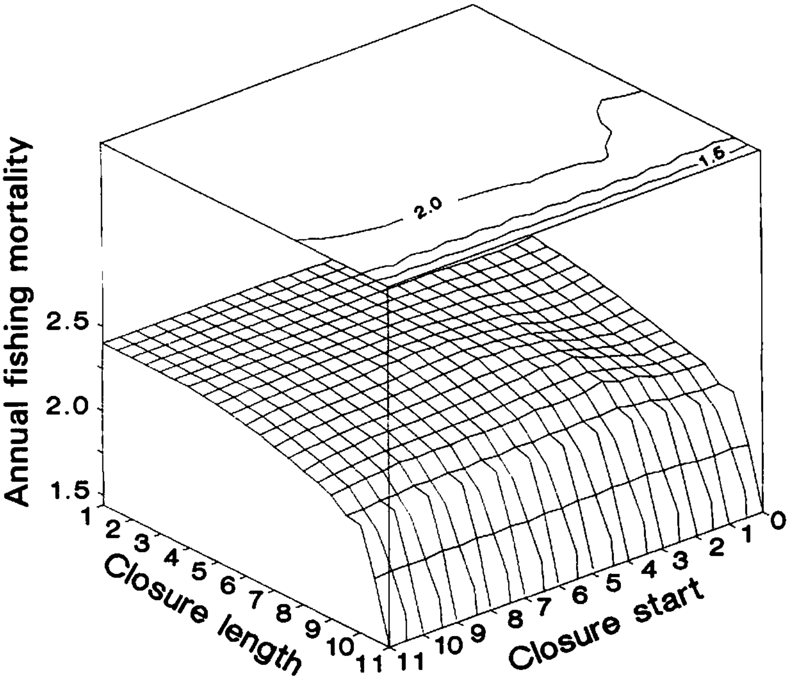

FIGURE 3.—Annual fishing mortality associated with fishing closures of different lengths (months) and different starting times (month of year) for a simulated tiger prawn fishery in Torres Strait, northern Australia.

All output criteria used—Y/R, V/R, and E/R—responded similarly to changes in the natural mortality multiplier, M_{mult} (Figure 5d). Reducing M_{mult} by 25% increased all output criteria by 55%; increasing M_{mult} by 25% decreased all criteria by 35%.

Discussion

The need for assumptions regarding the response of fishermen to new regulatory controls poses problems to the evaluation of fisheries management regulations (Sluczanowski 1984). Fortunately, in this study logbooks provided data on fishing effort over a series of years in which seasonal closures of different duration had occurred. Analysis of these data was used as a basis for modeling changes in the fishing effort patterns associated with closures. Analysis of population survey data also provided information on the relationship between recruitment timing and patterns of fishing effort.

Fishing effort patterns are determined by the interaction between operational, economical, and biological factors. In penaeid shrimp fisheries the pattern of recruitment to the fishery largely determines the pattern of effort (Garcia 1985). This is a result of the combination of very high exploitation and natural mortality rates and a short lifespan. Catches tend to be highly correlated with recruitment levels interannually and within a season (Watson et al. 1990a). It is, therefore, a thesis of this paper that changes in the seasonal recruitment pattern caused by the imposition of a fishery closure will change the pattern of fishing effort.

Shrimp fishery closures induce pulses of effort at the opening of the fishing season (Watson et al. 1990a; Dredge and Gribble 1991). It is unclear, however, whether closures reduce or increase annual fishing effort (Nichols 1982). Pulses of effort at the season's opening presumably reflect fisherman's expectations for increased biomass resulting from the closure event. It follows then that expectations of high accumulation of biomass will be associated with stronger pulses. In the present model, fishing pulse strength is determined by the length and timing of the closure. The longer and better-timed the closure, the higher the expected accumulated biomass, and the stronger the pulse of fishing effort in response.

Basic differences in the management of any shrimp fishery will affect potential gains from seasonal closures. Australian shrimp fisheries are not open access as are those in the Gulf of Mexico; thus problems associated with the redirection of

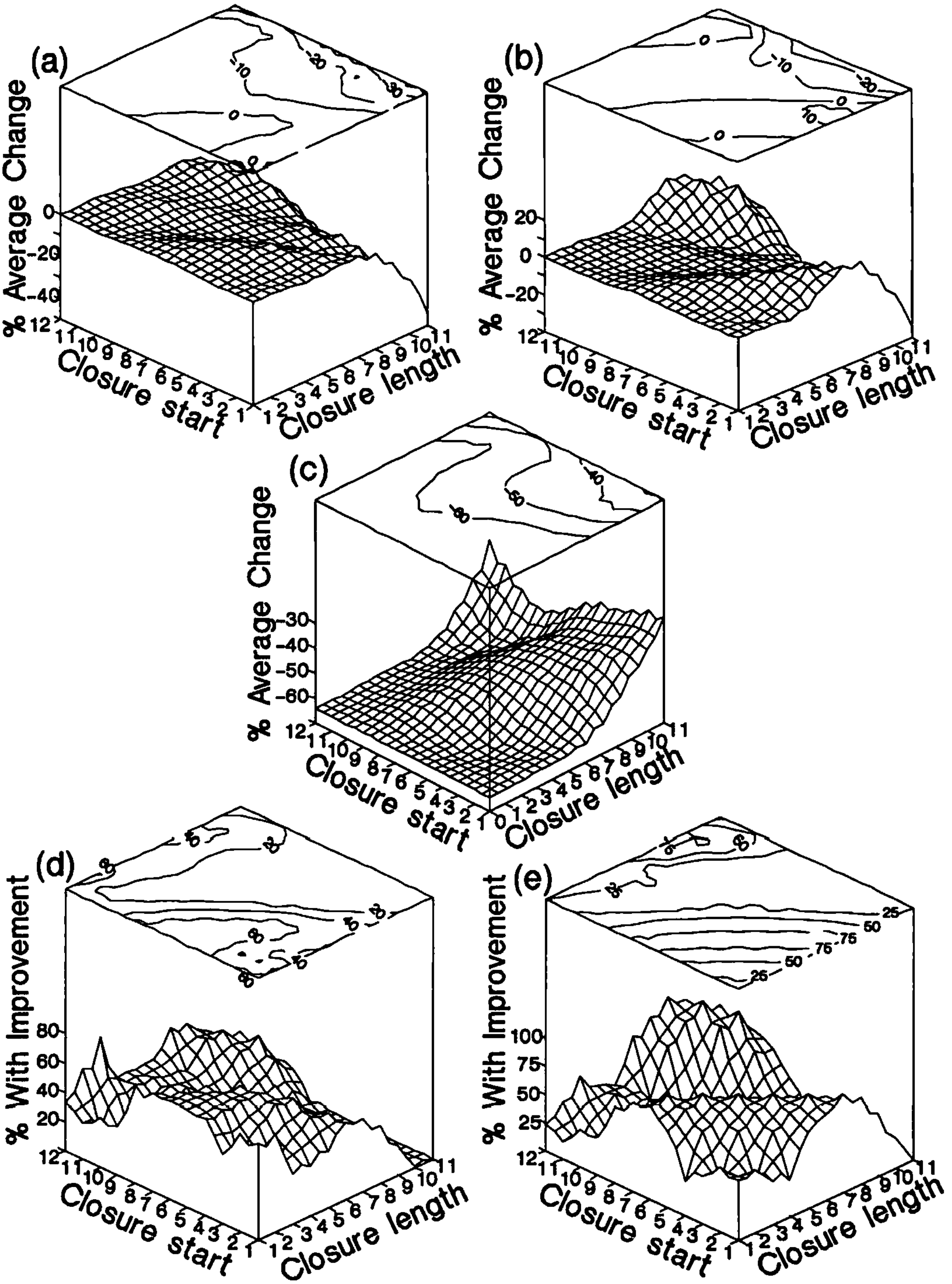

FIGURE 4.—Changes caused by the imposition of closures with different lengths (months) and different starting times (month of year) predicted by a simulation model of the Torres Strait tiger prawn fishery in northern Australia. Changes are relative to simulations without a closure. Shown are average percentage changes in (a) yield per recruit, (b) value per recruit, and (c) eggs per recruit. Also shown are percentages of simulations that resulted in improvements in (d) yield per recruit and (e) value per recruit compared to simulations without closures.

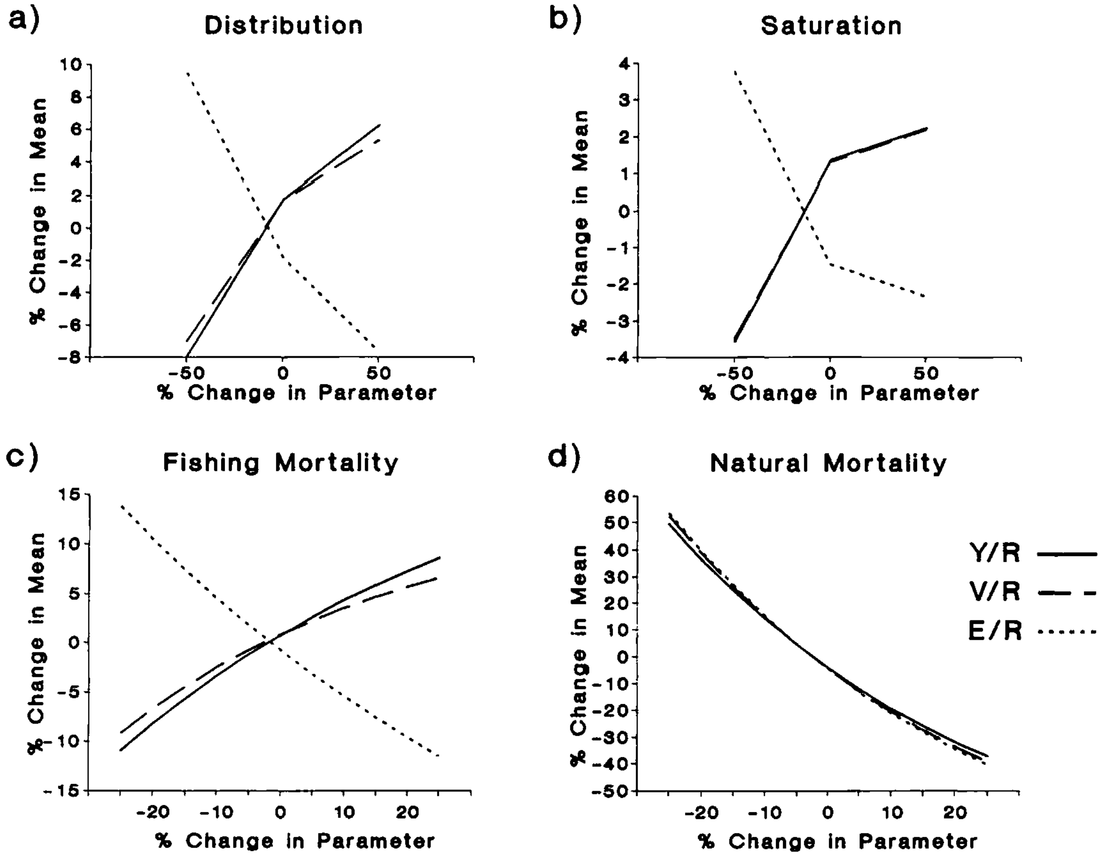

FIGURE 5.—Sensitivity of predictions from a simulation model of the Torres Strait tiger prawn fishery in northern Australia to various model parameters. Percent changes in the average yield per recruit (*Y/R*, solid line), average value per recruit (*V/R*, dashed line), and average eggs per recruit (*E/R*, dotted line) are given as functions of percent changes in **(a)** effort redistribution parameter, *d*; **(b)** effort saturation parameter, *r*; **(c)** fishing mortality multiplier, F_{mult}; and **(d)** natural mortality multiplier, M_{mult}.

fishing effort might initially seem to be of lesser importance. There are, however, parallel problems in northern Australia, where there are three distinct, separately managed, shrimp fisheries: the northern fishery in the Gulf of Carpentaria, the Torres Strait fishery, and the Queensland east coast fishery. Vessels may be entitled to fish in all three or may be restricted to only one. Thus, instead of redirection of fishing effort between the inshore and offshore fisheries as experienced in the Gulf of Mexico, in Australia there is redirection of effort between these different, geographically separated fisheries. Nance et al. (1988) described the influence that closures in Gulf of Mexico shrimp fisheries may have on adjacent fisheries. Similarly, seasonal closures of shrimp fisheries in northern Australia affect one another. Fishermen denied access to their fishery through a seasonal closure resent fishermen who continue fishing elsewhere and then arrive when the closure ends and shrimp catches are optimum. This interaction has forced modifications to the timing of closures, generally resulting in similar dates for the commencement of fishing in adjacent fisheries. As a result, in some Australian shrimp fisheries, recent closure durations and timings have been dictated more by the effects of interacting, adjacent fisheries than by optimal-harvest considerations for the individual fisheries.

Unlike the U.S. fishery in the Gulf of Mexico, however, the number of vessels in these Australian fisheries is restricted, and in fact, industry-funded schemes in the northern fishery have lead to a reduction in vessel numbers through paid voluntary retirement. In the Torres Strait there are currently 120 licensed vessels, and no new entitlements will be issued. All these vessels are also entitled to fish in the east coast fishery, and some are also entitled to fish in the northern fishery. Seasonal closures currently exist in all three fisheries. If a seasonal closure of the Torres Strait fishery makes it more attractive than competing fisheries, then more fishing effort will be spent in this fishery, particularly in the weeks immediately after the season opens, and will result in the observed pulse of fishing effort. The limited number of vessels entitled to fish in Torres Strait, however, constrains any increase in fishing effort, which we reflect through our use of a saturation parameter in our simulation model. In such a management environment the expected benefits from a seasonal closure will accrue primarily to vessels already in that fishery rather than be dispersed by attracting new vessels. The potential for attracting new vessels to the fishery would force a decision on whether the management goal was to maximize the value of the fishery in general or to maximize the value to the vessels currently involved in the fishery.

Although accumulation of biomass is certainly an incentive for fishermen to fish, market forces and operational constraints may ultimately control how a fishing fleet reacts. For instance, the Torres Strait penaeid fishery is managed under a license system, and therefore, there is an upper limit to the amount of fishing effort the fleet can put in any month. This is the reason why a saturation parameter was incorporated in the present model and why it is operationally unlikely that the present peaks in monthly fishing effort could be multiplied by more than a factor of four ($r = 4$), no matter what type of closure is imposed. In addition, the saturation parameter may also be used to model a reduction in catchability that could occur when the density of operating fishing boats increases to levels where boat density either affects trawling efficiency due to gear competition or induces changes in prey behavior.

Seasonal price fluctuations can also affect the seasonal effort pattern because price partially determines profit margins in the fleet. Shrimp prices in the Torres Strait fishery, however, are determined by fluctuations in the international commodity market, thus shrimp prices in Torres Strait are considered relatively insensitive to changes in local production. Other authors have made a similar assumption when faced with modeling shrimp fishery prices (e.g., Dashti and Mathews 1987).

Simulation can provide managers with expectations of how management measures will affect the yield and value of a fishery. If a realistic level of input parameter uncertainty is incorporated, simulations can also be used to provide not only point estimates but some estimate of precision as well (Restrepo and Fox 1988). Our example indicates that if the Torres Strait shrimp fishery were closed for approximately 6 months starting in December or January then a 5–10% increase in the value of the fishery could be expected. Over the wide ranges of mortality parameter values used, this type of closure would have a 75% chance of improving the value of the fishery compared with an open fishery (conditional on the recruitment and growth parameters being known precisely). Conversely, there is also a 25% chance that this management strategy would actually decrease the value of the fishery. Wide ranges of values for parameters such as natural mortality were deliberately used in our simulation. Typically our knowledge is imprecise, and the values of such parameters may vary considerably from year to year. Watson and Restrepo (in press) showed that assumptions about recruitment can greatly affect predicted gains from seasonal closures. If the recruitment process were more discrete than that which we assumed, such as a single monthly cohort, the predicted gains would have been higher but the timing of the best closure more critical. If recruitment were a more protracted and continuous process than we assumed, or if differing species-specific recruitment patterns in a multispecies fisheries were considered, then predicted gains would be less and all possible closures might reduce the value of the fishery. Results framed in this fashion remind managers that there is not a single predicted outcome from a management decision but rather potentially a whole complex distribution of outcomes.

Acknowledgments

Support for this study was provided by the Queensland Department of Primary Industries and the Queensland Fish Management Authority and through the Cooperative Institute for Marine and Atmospheric Studies by National Oceanic and Atmospheric Administration cooperative agreement NA90-RAH-0075.

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