

MARINE RESERVES AND MANAGEMENT OF THE NORTHERN CALIFORNIA RED SEA URCHIN FISHERY

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ABSTRACT

Catch in the northern California red sea urchin fishery has declined from 14,000 metric tons in 1988 to less than 1,000 in recent years. Although the institution of marine reserves is not expected to restore catch to former levels, reserves at least have the potential to prevent further decline. The answer to the question of whether reserves would benefit this fishery depends on an essential uncertainty in recruitment, which we model as a parameter in a Beverton-Holt relationship between number of larvae produced and successfully settling juveniles. For high values of the slope of this function at the origin, recruitment is relatively impervious to fishing, and the addition of reserves diminishes catch. For low values of this slope, fishing decreases recruitment, and the addition of reserves increases catch by increasing recruitment. A decision analysis accounting for the distribution of possible values of this slope indicates a benefit in long-term equilibrium catch of 18% with one-sixth of the coast in reserves. However, accounting for short-term losses due to the initial implementation of the reserves by considering only catches over the first 50 years reduces this gain to 12%. This figure is sensitive to the relative value of short-term and long-term gains, and to the rate at which reserves are implemented.

INTRODUCTION

Marine reserves have been proposed as a possible remedy for the perceived problems associated with the decline in catch of the northern California red sea urchin fishery (fig. 1). It is generally believed that much of the decline was due to "fishing up" an unexploited stock (Botsford et al. 1999); thus reserves are not expected to restore the original catch levels. However, there is still concern that the population is in danger of further decline caused by a decrease in recruitment, and some believe that the institution of reserves could avert that decline. Here we attempt to answer the fundamental question: Given our current understanding of this fishery, will the institution of marine reserves lead to greater future catch than we would otherwise have?

Because the consequences of fishery management by marine reserves are complex and still poorly understood, we focus our answer to this question on a few essential mechanisms. We pose the question in terms of fishery management, and evaluate management only in terms of greater or lesser catch. We do not address other benefits of marine reserves, nor do we consider larval dispersal and the optimal spacing and configuration of the reserves. We also do not address other possible fishery management measures such as changes in fishing effort and size limits. All of these are unnecessary in answering the basic question posed, and each can be answered in other studies that make use of the results obtained here.

The cause of the decline in northern California is reasonably well understood, and enough is known about the life history of the red sea urchin to begin to evaluate the design of reserves. The red sea urchin fishery developed rapidly in the late 1980s as a result of a shift in the exchange rate of the Japanese yen and the ready availability of urchin divers from the southern California fishery (Kalvass and Hendricks 1997). Since that time catch has declined rapidly, as would be expected from the initial exploitation of an unfished population (Botsford et al. 1999).

Growth and both natural and fishing mortality rates are well known (Morgan 1997). Much is known about recruitment, such as the dependence of fecundity on size, and the influence of coastal circulation on settlement patterns (Morgan 1997). Some density-dependent mechanisms are known, such as the protection of juveniles under the spine canopy of adults (Tegner and Dayton 1977) and the decreasing efficiency of broadcast spawning (Leviton et al. 1992). However, survival through the larval stage, and the origin of recruits to each location are not known.

Marine reserves are currently of great interest because of their potential as a tool for combating overfishing and preserving declining marine biodiversity (e.g., Botsford et al. 1997; Murray et al., in press; and other papers in this symposium). But so far, reserves are poorly

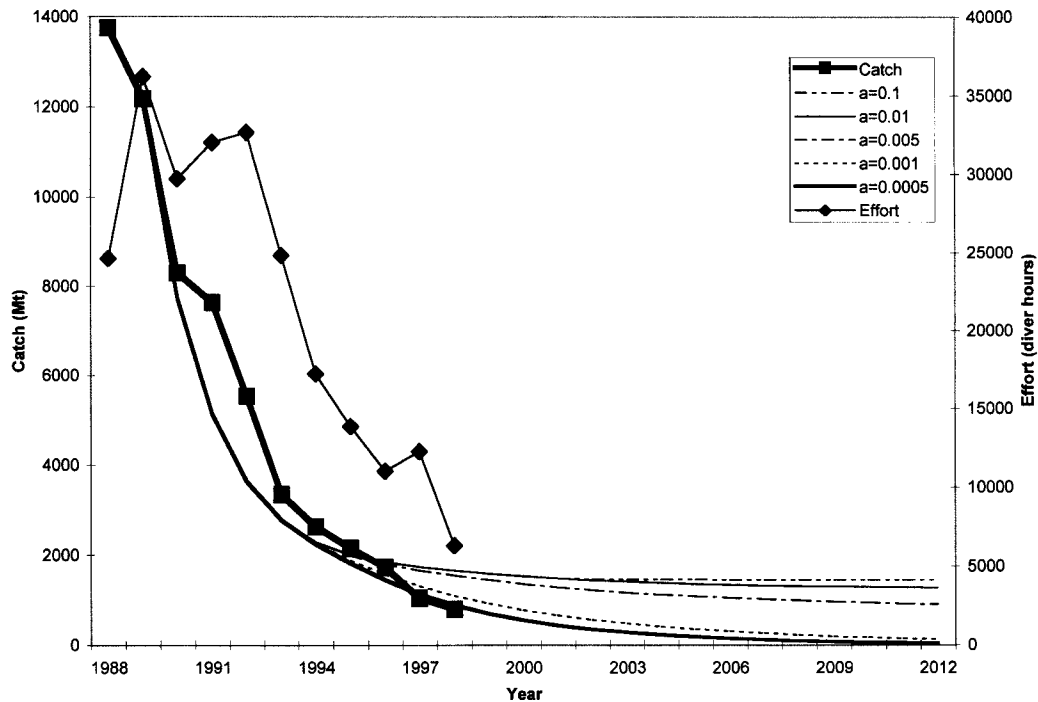


Figure 1. Catch in the northern California red sea urchin fishery from 1988 and catch from the red sea urchin model with constant fishing mortality rate and different values of a , the slope of the Beverton–Holt relationship between successfully settling juveniles and competent larvae at each location. The declining effort is also shown.

understood. With regard to fisheries management, they have been proposed for preventing overfishing in the presence of parameter uncertainty (Clark 1996; Botsford et al. 1997; Lauck et al. 1998); for providing greater fishery yields when effort is high (Quinn et al. 1994; Sladek-Nowlis and Roberts, in press); and for reducing variability in catch (Sladek-Nowlis and Yoklavich 1998; Sladek-Nowlis and Roberts, in press). Quantitative analyses of the effects of reserves in a fishery context have involved issues such as how reserves reduce uncertainty (Lauck et al. 1998); the effects on harvested cohorts of migration (Polacheck 1991; DeMartini 1993); and the performance of reserves in conjunction with standard fishery management (Quinn et al. 1994; Sladek-Nowlis and Yoklavich 1998; Sladek-Nowlis and Roberts, in press).

MODEL

To answer the question of whether reserves can lead to greater catch, we use a model that we have developed as a tool for answering the many questions associated with instituting reserves in the management of the northern California red sea urchin fishery. The model consists of 24 independent, size-structured subpopulations linked in the larval stage by a dispersal matrix representing all combinations of larval origins and destinations. We model each subpopulation by using von Bertalanffy growth with intrapopulation variability in L_{∞} . Parameter values for growth, natural mortality, and

fishing mortality vary along the coast (Morgan 1997), but for our purposes here we use typical values. These values were estimated from data collected in the Bodega Marine Reserve: $L_{\infty} = 118$ mm; the standard deviation of $L_{\infty} = 10$ mm; the von Bertalanffy growth parameter $k = 0.22 \text{ y}^{-1}$; and natural mortality rate $M = 0.08 \text{ y}^{-1}$.

The nature of density-dependence in the recruitment process is critical to the question asked here. Density-dependence in fecundity occurs in sea urchins, but typically only at the densities of urchin barrens (Leviton 1989). Density-dependence in the larval stage is not known, but is not suspected to occur, since larval sea urchins would be a relatively unimportant consumer in the planktonic food web. It is likely that there is an upper limit on settlement density or early survival and that it is determined by the amount of available habitat. The essential limiting characteristic of the habitat would be the provision of structure for protection against predation. Similar mechanisms have been studied in benthic crustaceans (Caddy 1986; Wahle and Steneck 1991) and reef fishes. Those mechanisms may involve adults or other settled, older stages, but any specific habitat is typically suitable for only a narrow range of sizes. Hence it is doubtful that the density of adults influences postsettlement survival of red sea urchins other than through the spine canopy mechanism noted above.

Because of these considerations we use a Beverton–Holt relationship to describe the dependence of success-

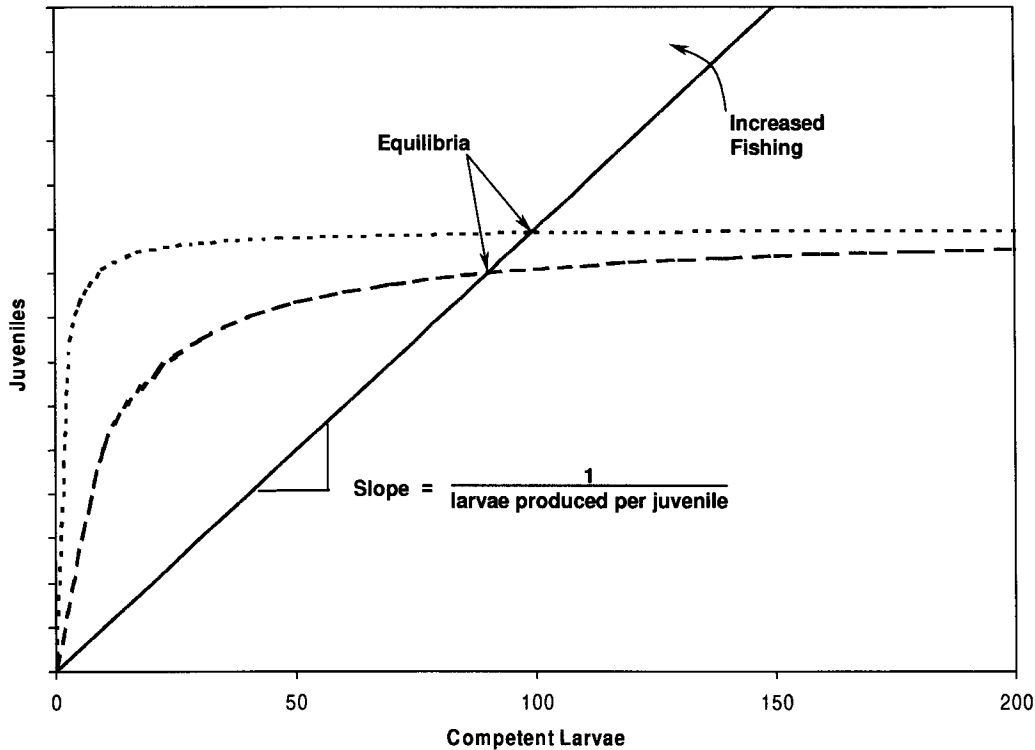


Figure 2. A schematic view of the model relationship between the number of juveniles successfully settling and surviving at a location, and the number of competent larvae attempting to do so, for two different values of the slope at the origin, a . The slope of the straight line is the inverse of the number of larvae produced in the lifetime of each settled juvenile, which increases as fishing mortality rate increases. The intersection of this line with the appropriate juvenile/larval line is the equilibrium rate of juvenile settlement.

ful settlement (S_t) on the number of larvae attempting to settle at each location (L_t):

$$S_t = \frac{L_t}{\frac{1}{a} + \frac{L_t}{C}} \quad (1)$$

where a is the slope at the origin, and C is the maximum value or juvenile carrying capacity (fig. 2; Beverton and Holt 1957). The value of C was assumed to be the same for each of the 24 subpopulations, and was set to a value that yielded the observed total catch in this fishery. Because the value of a is unknown, we evaluated a range of values. For a fishery without reserves, equilibrium recruitment is the intersection of the Beverton-Holt curve describing the number of settling juveniles versus competent larvae, and a straight line whose slope is the inverse of the number of competent larvae produced in the lifetime of each successfully settling juvenile (fig. 2). As fishing mortality increases, larvae produced per juvenile decreases, and equilibrium recruitment declines (fig. 2). The equilibrium value of recruitment declines more rapidly for the juvenile/larval relationship with the smaller value of a .

The two other known density-dependent mechanisms involved in recruitment are included in this analysis only indirectly. The effect of adult spine canopy as a refuge

from predation for juveniles (Tegner and Dayton 1977) is proportional to the number of adults, hence it would be a linear mechanism rather than a depensatory mechanism, and it is reflected approximately in the dependence of egg production on adult numbers, which directly influences the value of a . Our analysis of the proposed Allee effect associated with broadcast spawning (Levitan et al. 1992; Lundquist and Botsford¹) has shown that below a certain adult density, egg production becomes highly variable, but the shape of the dependence of mean recruitment on adult density does not exhibit a threshold; instead, it is approximately linear. Here we include that effect only as greater uncertainty in recruitment (as reflected in the value of a).

Our current understanding of how coastal circulation transports sea urchin larvae to their location of settlement indicates a specific spatial pattern of settlement each year, but the pattern is variable enough that we assume larvae are mixed and some settlement reaches all areas. Samples from settlement collectors and benthic size distributions indicate that red sea urchins tend to settle in greater abundance just to the north of major promontories (Morgan and Botsford 1998). This view is consis-

¹Lundquist, C. J., and L. W. Botsford. Stochastic Allee effects due to reduction in invertebrate density by a fishery. (manuscript)

tent with a mechanism for retention of invertebrate larvae in features associated with capes and points during active upwelling (Wing et al. 1998) and subsequent delivery of invertebrate larvae to settlement sites by poleward, on-shore flow during upwelling relaxation (Wing, Botsford et al. 1995; Wing, Largier et al. 1995; Morgan and Botsford 1998). The effect of this spatial pattern on the fishable adult abundance has not yet been clearly demonstrated, and the amount of exogenous input of larvae carried by dominant currents from the north is unknown.

To maintain the focus of our analysis here on the simple question of whether reserves increase catch, we assume that all larvae produced by the 24 subpopulations are completely mixed and uniformly redistributed along the coast, and we set the dispersal matrix accordingly. Studies in which larval dispersal patterns and reserve configurations are explicitly included have indicated that this is a good approximation to a wide variety of situations (Botsford and Hastings²).

RESULTS

Under the model conditions described here, the efficacy of reserves depends critically on the value of the parameter a , the slope of the relationship between competent larvae and successfully settling juveniles (see equation 1 and fig. 2). As the amount of area placed in reserves increases from 1 of the 24 subpopulations, to 1 every 12 subpopulations, 1 every 8, 1 every 6, and 1 every 4 subpopulations, equilibrium catch either increases then decreases, or decreases monotonically (fig. 3). For high values of a , settlement will maintain a high, constant value regardless of how fishing affects total egg production and the number of larvae produced (fig. 2). In this case, reserves contribute nothing to future recruitment, and their only effect is to remove the reserve areas from access by the fishery. For low values of a , the equilibrium value of number of larvae successfully metamorphosing and settling without reserves is low, and placing parts of the coast in reserves increases total egg production and larval production. Catch increases to the point that adding more reserves no longer increases recruitment, then declines for the same reason it does with high values of a : areas are removed from access by the fishery.

This poses a problem that will be present in any analysis of the efficacy of reserves in this fishery, no matter how many other mechanisms and factors are considered; namely, that the advisability of reserves depends critically on the value of the parameter a , which is unknown. In many similar situations in fisheries (Hilborn and Walters 1992), conservation biology (Ralls and Starfield 1995), and resource management in general, similar decisions

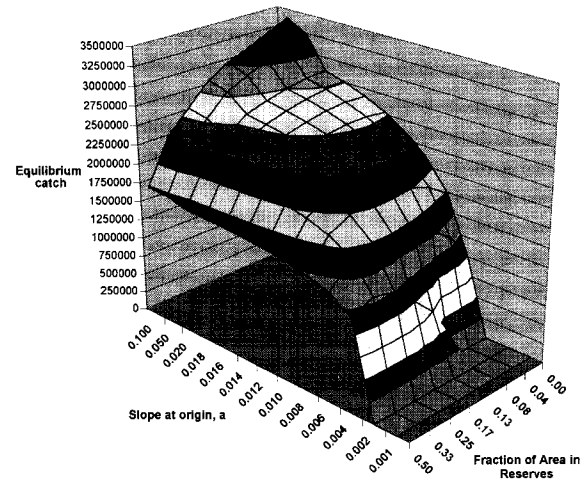


Figure 3. Equilibrium catch versus the fraction of coastline in reserves, for various values of a .

involving uncertainty are made by using formal decision analysis. In its simplest form, decision analysis involves (1) evaluating how the system of interest responds to various management options (e.g., fraction placed in reserves) under a variety of reasonable assumptions regarding the possible (but unknown) states of nature (e.g., values of a); and (2) comparing how well each decision performs across the range of possible states of nature. We accomplished the latter by computing the mean performance over the distribution of states of nature (e.g., the probability distribution of a). To do so, we first needed to assess how likely each value of a is, based on the information currently available.

One source of information regarding the possible values of a is the catch record itself. Comparing actual catch with catch from the model with constant fishing mortality ($F = 0.5$) for various values of a indicates that the decline in model catch matches the actual decline quite well up to 1998, regardless of the value of a (fig. 1). However, after 1998 actual catch seems to decline more rapidly than model catch for any values of a . This could be due in part to a decline in fishing mortality rate caused by the general reduction in effort with the decline in abundance, but mortality rate need not decrease in proportion to abundance. Catch also would be influenced by market conditions; for example, it is known that the exchange rate between the Japanese yen and the dollar shifted by about 20% in 1997 and 1998. If we ignore the corresponding dip in catch in 1997, the slope of the actual catch trend from 1993 to 1996 most closely matches the lower model projections, indicating that the value of a could be as low as 0.001.

A second source of information on the value of a can be obtained by comparing the decline in fishable abundance, as reflected in CPUE, to the expected decline in fishable abundance due to the fishing up effect, as

²Botsford, L. W., and A. Hastings. Sustainability of populations in marine reserves. (manuscript)

TABLE 1
 The Expected Values of Improvements in Fishery Performance as the Area in Reserves Increases

No. of subpopulations (Percentage of coastline)	0 in 24 (0%)	1 in 24 (4.17%)	2 in 24 (8.33%)	3 in 24 (12.50%)	4 in 24 (16.67%)	6 in 24 (25%)	8 in 24 (33%)	12 in 24 (50%)
Equilibrium catch	1.00	1.08	1.11	1.17	1.18	1.14	1.06	0.85
50-yr catch	1.00	1.04	1.09	1.11	1.12	1.10	1.04	0.87
Discounted 50-yr catch	1.00	1.01	1.04	1.04	1.02	0.98	0.92	0.74

Note: The assumed distribution of a is probabilities of 0.1, 0.1, 0.2, 0.2, and 0.1 for $a = 0.001, 0.002, 0.004, 0.006, \text{ and } 0.008$, respectively, and a probability of 0.05 for $a = 0.010, 0.012, 0.014, 0.016, 0.018, \text{ and } 0.020$. The discount rate is 0.03 y^{-1} .

reflected in the size distribution of the catch (Botsford et al. 1999). For that analysis we computed the decline in CPUE that would be expected from the change in the size distribution assuming constant recruitment; we then compared that over the years 1988 to 1994 to the decline in CPUE at the four major ports in the northern California fishery. We found that in three of the ports CPUE declined faster than expected, but was statistically significant in only one port. This implies that there has been a decrease in recruitment since the advent of the fishery, at least at some points along the coast, which would indicate that the value of a for the population as a whole is near the value which would cause a long-term decrease in recruitment.

A third source of information on the value of a is values observed for fisheries in general. To minimize the chance of collapse due to overfishing, fishery biologists maintain the relative egg production per recruit above a certain level. The relative value of egg production per recruit is the ratio of egg production in the lifetime of an average female under current fishing to egg production without mortality due to fishing. Below a threshold level, which ranges from 0.20 to 0.35 and higher, a stock is declared overfished and steps are taken to reduce fishing mortality (Goodyear 1993; Mace and Sissenwine 1993; Rosenberg et al. 1994). In our model this parameter would be proportional to the value of a . The value of relative egg production per recruit for the northern California red sea urchin, assuming $F = 0.5$, is near 0.20, the lowest value of the overfishing threshold.

A decision analysis with a distribution of values of a based on these considerations suggests that the maximum expected equilibrium catch would be realized with 20% of the coast in reserves (table 1). For the distribution of a , we assumed that a was most likely to be near 0.004 or 0.006, but could be as high as 0.02. Specifically, we hypothesized that a was uniformly distributed between .01 and .02 inclusively; was twice as likely to have values of .008, .001, and .002; and was twice again as likely to have values of .004 or .006 (see table 1 note for probabilities). The gain in expected value of equilibrium catch with reserves was roughly 18% (table 1). Some of

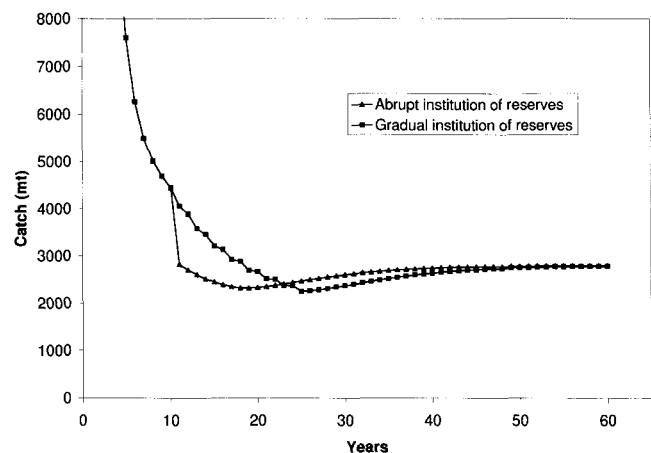


Figure 4. For a value $a = 0.008$, the abrupt decline in catch when one-third of the coast (eight reserves) is placed in reserves 10 years after a fishery is initiated (triangles), and the more gradual change in catch when the eight reserves are instituted gradually (squares).

the possibilities used in computing the expected value of catch involved zero catch without reserves ($a = .004$), and no catch even with reserves ($a = .002$ and $a = .001$), i.e., indicating a collapsed population (fig. 3).

This analysis omits an aspect of model behavior observed in the simulations that will be important for implementing reserves—namely, the immediate decline in catch in the years after the reserves are instituted. The performance in figure 3 is long-term equilibrium catch, which ignores the short-term economic effects of instituting reserves (fig. 4) and any differences in those effects between the various values of a . The dependence of these adjustment costs on the value of a is significant. In particular, even though the long-run catch may be greater at low values of a , catch recovers much more slowly after the institution of reserves. These short-term effects can be included in the decision analysis by computing catch over the first 50 years rather than eventual equilibrium catch (table 1). In that case fewer reserves are indicated as the best choice, and the expected value is close to the optimal over a broader range.

Another way of accounting for the relative value of near-term versus long-term catches is to discount future

catches. With a discount rate of 0.03 y^{-1} , the optimal fraction in reserves shifts to fewer reserves; the optimal is even broader; and the gain through reserves is slight—4% as opposed to 12%. However, the large initial decline in catch can be reduced by phasing in reserves gradually (fig. 4).

DISCUSSION

The results described here illuminate the fundamental uncertainty that underlies the question of whether marine reserves can benefit management of the northern California red sea urchin fishery. That fundamental uncertainty is the same one that underlies the prevention of overfishing in fisheries throughout the world: as fishing increases, the number of larvae produced in the lifetime of a juvenile may eventually be reduced to the point that there is a decline in recruitment, but, because we have little or no data at low abundance (i.e., to the left in fig. 2), we do not know the value of the fishing mortality rate at which that will occur. Here we have outlined some of the difficulties involved in determining whether this population is recruitment overfished, but there is more information available for this population than for most others. For world fisheries in general, data are rarely available on the decline of a developing fishery or the size distribution as a fishery develops (Caddy and Mahon 1995).

The efficacy of reserves as a management tool depends on whether this population is currently overfished or is likely to become overfished in the near future. The several lines of evidence on this issue vary in strength. Comparison of the decline in catch to model runs under various assumed values of a provides compelling evidence, but suffers from the fact that we have no way of estimating how fishing mortality rate varies from year to year. We do not know whether the recent declines in catch are due to declining abundance at constant fishing mortality rate or declining fishing mortality rate. Effort has declined (fig. 1), but as abundance declines, the amount of effort required to remove a certain fraction of urchins from the smaller population will decline. Hence it is reasonable to expect a decline in effort even at the same fishing mortality rate. Changes in the exchange rate between the yen and the dollar also would be expected to influence catch. The comparison of the decline in CPUE expected from the change in the size distribution (Botsford et al. 1999) involves fewer assumptions, and thus provides stronger evidence of a decline. Placing the current value of relative egg production per recruit in the context of threshold values of that parameter in fisheries management on a global scale provides greater generality to this argument, but suffers from the fact that few of the species being considered in the assessment of safe targets were invertebrates.

While our results provide information on the dynamic interactions between parameter values and the consequences of reserves, they are not completely definitive, because we have not addressed all of the many issues relevant to this question. We have only indirectly included the effects of low density on broadcast spawning (Leviton et al. 1992). Recent research indicates that the combined effects of reduced density and aggregation on broadcast spawners produce specific stochastic as well as deterministic effects on recruitment (see footnote 1). The interaction of temporally and spatially varying dispersal patterns with reserve configuration is another area for further analyses.

We also have assumed no change in fishing mortality with the institution of reserves. This omits two important issues that deserve further consideration. First, if reserves are instituted, they will obviously affect the decisions of divers as to when, whether, and where to fish. Ongoing research on this issue will provide estimates of changes in effort patterns that will have to be considered in evaluating the efficacy of reserves. The second issue to be evaluated is how it would be best to change fishing mortality rate as reserves are instituted. Preliminary indications are that it is optimal to increase fishing mortality rates when reserves are instituted. Evaluation of this issue would include the necessary consideration of how well potential overfishing might be remedied by changing effort or size limits rather than by instituting reserves (Hastings and Botsford 1999; Parrish 1999). Another issue on which more information is needed is the possibility of predispersal density-dependence in reserves. Assessing such effects in the few, small, red sea urchin reserves that currently exist would be a valuable first step.

The decision of whether to institute reserves in this fishery will involve the response of managers to the uncertainty described here. There is no guarantee that reserves will increase catch; in fact, if reserves are instituted there will be no way to tell whether they increased catch over what it would have been. Recent global analyses of the causes of widespread overfishing have indicated that precautionary, more risk-averse strategies are needed (Ludwig et al. 1993; Botsford et al. 1997). The precautionary approach to fishery management involves a shift in the burden of proof, which in this case would indicate that reserves should be instituted unless it could conclusively be demonstrated that the fishery could persist without them.

The eventual decision of whether to institute reserves will depend on a broader range of considerations than addressed here. If one considers effects beyond the management of the fishery on this species, reserves can serve a more general function of preserving natural biodiversity in a more or less pristine state. Even within the con-

text of fishery management, two benefits of reserves not usually considered are that (1) management by reserves involves fewer uncertain assumptions about the effects of fishing on population dynamics (e.g., Clark 1996), and (2) maintaining part of the fished species in an unfished state has value for informational purposes. As an example of the latter, in fisheries for which the ages of individuals cannot be determined, size-structured approaches to stock assessment require unfished stocks for estimation of natural mortality rate (Morgan 1997).

The results of our analysis can be viewed as the reserve concept passing a simple initial test. What remains is to assess other issues not considered here. These include (1) how other density-dependent recruitment mechanisms affect expected catches; (2) fishers' behavior in response to spatial management; (3) possible spatial configurations of reserves implied by dispersal patterns; and (4) the advisability of making other concurrent management changes, such as changing size limit in addition to adding reserves.

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