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IMPLEMENTING THE PRECAUTIONARY PRINCIPLE IN FISHERIES MANAGEMENT THROUGH MARINE RESERVES

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Abstract. Overexploitation of marine fisheries remains a serious problem worldwide, even for many fisheries that have been intensively managed by coastal nations. Many factors have contributed to these system failures. Here we discuss the implications of persistent, irreducible scientific uncertainty pertaining to marine ecosystems. When combined with typical levels of uncontrollability of catches and incidental mortality, this uncertainty probably implies that traditional approaches to fisheries management will be persistently unsuccessful. We propose the use of large-scale protected areas (marine reserves) as major components of future management programs. Protected areas can serve as a hedge against inevitable management limitations, thus greatly enhancing the long-term sustainable exploitation of fishery resources. Marine reserves would also provide an escape from the need of ever more detailed and expensive stock assessments and would be invaluable in the rehabilitation of depleted stocks.

Key words: bet hedging; controlling overexploitation; diversification; fisheries; irreducible scientific uncertainty; marine protected areas; marine reserves; precautionary principle in fisheries; risk aversion.

INTRODUCTION

In 1982, the United Nations (U.N.) Third Conference on the Law of the Sea closed and formally ushered in a new era in world fisheries management through the Law of the Sea Convention (United Nations 1982). Under the Convention, coastal states throughout the world were enabled to extend their management jurisdiction over fishery resources from 12 to 200 (22.2 to 370.4 km) nautical miles. It was estimated that 90% of the harvests of marine fishery resources would be accounted for by resources encompassed by the coastal state 200-mile (370.4-km) zones—Exclusive Economic Zones (EEZs; Kaitala and Munro 1995). The objective in establishing the EEZ regimes was to enhance the conservation and economic management of world marine fishery resources. In 1980, a Food and Agricultural Organization of the United Nations (FAO) publication, in anticipation of the EEZ regime, stated that: "the opportunity exists, as never before, for the rational exploitation of marine fisheries. . . . The 1980s provide the threshold for a new era in the enjoyment of the ocean's wealth in fisheries" (cited in United Nations Food and Agriculture Organization 1992).

The hopes and expectations of the early 1980s have not been realized. The same FAO recently reported that "69% of the world's marine [fish] stocks . . . are either fully to heavily exploited, overexploited, depleted . . . and therefore are in need of urgent conservation and management measures" (United Nations Food and Agriculture Organization 1995). Coastal state fishery management programs have proven, in far too many instances, to be seriously deficient.

One of the most dramatic and depressing examples of fishery management failure under the EEZ regime is provided by the large and extremely productive groundfish resources on the famous Grand Banks of Newfoundland, which constituted Canada's main bonanza under the EEZ regime. These resources had been overexploited while international common property. Under conservative Canadian management, it was hoped that fish stocks would be rebuilt, to the benefit of the Canadian fishing industry. The single most important of these resources, a cod stock complex extending from southern Labrador to southeastern Newfoundland, popularly known as Northern cod (*Gadus morhua*), was expected to yield sustainable annual harvests of 4×10^8 kg by the late 1980s (Canada 1983).

These sustainable harvests were not achieved. In the late 1980s, the Canadian government introduced drastic cuts in the Northern cod total allowable catches (TACs). The drastic TAC cuts were not enough. In 1992, the Canadian authorities felt compelled to impose a temporary 2-yr harvest moratorium on Northern cod.

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The authorities were horrified to find that the resource continued to decline after the moratorium had been imposed. The harvest moratorium still remains in place (in 1996) and has ceased to be temporary. It is now indefinite. To compound the misery, the Canadian authorities have had to impose harvest moratoria on several neighboring groundfish stocks.

The causes of the fishery resource collapse off Atlantic Canada are now the subject of an intense debate (Myers et al. 1997). What is clear is that the collapse came as a stunning shock to the authorities. One commentator remarked that the resource collapse would have had no credibility as a worst-case scenario, even a few years prior to the imposition of the moratorium (Roy 1996). What is equally clear is that the management of even seemingly stable fishery resources, such as groundfish, is subject to a far greater degree of uncertainty than heretofore had been realized and appreciated (Gordon and Munro 1996).

Standard Prescriptions for Correcting Management Failures

Suggestions for improving the management of marine fisheries have not been in short supply. We will not review here the long history of discussion of the "problem of overfishing," but will concentrate instead on the implications of uncertainty in fisheries management.

We take as an underlying assumption that fishery declines and collapses result in large part from overfishing, that is to say, from a level of fishing intensity that is excessive in terms of maintaining a sustainable population and fishery. We nevertheless recognize that changes in the marine environment are also often involved in the decline or collapse of any particular fishery. Levels of catch that may be sustainable under normal or favorable environmental conditions may prove not to be sustainable under abnormal conditions. Many fish populations that have suddenly collapsed under intensive exploitation had presumably persisted for thousands of years in spite of fluctuations in the marine environment. The parsimonious assumption is, therefore, that fishing decreased the resilience of these populations, rendering them more vulnerable to environmental change. From our perspective, this still constitutes overfishing.

Environmental fluctuations are but one of many sources of major uncertainty in fisheries. It is now widely accepted that management must somehow allow for uncertainty and potential inaccuracy in projected sustainable catch levels. It is our contention in this paper, however, that the full implications of uncertainty have not been recognized in the design and implementation of fisheries management strategies. This shortcoming, we believe, has been a major factor in the decline and collapse of many fisheries.

It is often suggested that uncertainty could be reduced if more research were to be undertaken. For example, increased stock assessment activity should keep management informed as to the current population size and its changes over time. While no one can dispute the need for stock assessment, it must be recognized that it is often very costly and that the estimates of stock abundance are almost always subject to considerable uncertainty. Many fish populations have become severely depleted before clear signals have appeared in the stock estimates. Fish stock assessment is now a highly developed and sophisticated science, but it is doubtful whether the levels of uncertainty can be greatly reduced by further refinements of technique. Fisheries science can and doubtlessly will continue to improve, but management decisions must depend on currently available methodology.

Accepting the inevitability of errors in sustainable catch estimates, fishery biologists have recently adopted management criteria that presumably err on the side of caution, a common example being the so-called $F_{0.1}$ criterion widely used in Canada and elsewhere. ($F_{0.1}$ is defined as the level of fishing mortality F at which the slope of the yield-per-recruit curve equals 0.1 times the slope at $F = 0$.) This criterion is more conservative than the maximum sustained yield criterion formerly favored, and as such allows for some degree of error.

But is the $F_{0.1}$ criterion sufficiently conservative? Walters and Pearse (1995) calculated that the $F_{0.1}$ value used in the Northern cod fishery, namely $F_{0.1} = 0.2$, would have to be reduced by 50%, to $F = 0.1$, in order to incorporate even a moderate degree of risk aversion in that fishery. ($F = 0.1$ means that 10% of the stock would be taken each year.)

Recommendations of this kind are based on the principle of erring on the side of caution, whether by maintaining catch levels or fishing mortality below estimated Maximum Standard Yield (MSY) levels, or maintaining stocks above the estimated MSY level (Roughgarden and Smith 1996). In essence these prescriptions are equivalent. Provided that such objectives can be reliably achieved in practice over the long term, sustainable fisheries will result. The question then becomes one of method and degree: how great a safety margin should be allowed, and which methods of management are most likely to achieve the objective of sustainable fisheries? For example, suppose that in a certain fishery stock estimates are considered valid to within ±30%, that annual productivity varies unpredictably over a range of ±50% from the mean, and that fishing plus incidental mortality varies within ±25% of the TAC. In the worst-case scenario, stocks are 30% below the mean estimate, productivity is 50% below the mean, and fishery-induced mortality is 25% greater than the TAC. To ensure sustainability, the TAC should then be set at 28% of the mean estimated value (this does not allow for any stock rehabilitation in the event that the stock is, in fact, below the mean estimate).

Such a safety margin may seem extreme. Indeed, the industry might argue in favor of the best-case scenario, with a TAC equal to 244% of the mean estimate. From this point of view, the original mean estimate TAC doesn't seem so bad, yet it is undeniably fraught with risk. This fanciful, but perhaps not quantitatively unrealistic illustration, raises several interesting issues. What levels of uncertainty exist in particular fisheries? How much can these uncertainties be reduced by additional research, or by tighter control of fishing operations? What is an appropriate safety margin? Will episodes of overfishing and underfishing balance out over the long run? Do estimation errors tend to be unbiased, in retrospect, or are worst cases more common than best cases? We know of no literature addressing such questions, which seem fundamental for the transition to sustainable fisheries when managed by traditional methods based on catch or effort quotas.

Uncertainty and Unknowability in Complex Systems

In this era of scientific wonders it is hard to avoid the "world view" of science as being ultimately capable of fully revealing and understanding the complexities of nature. This view is encountered frequently in fisheries in terms of recommendations for more scientific research into the functioning of marine ecosystems. Thus, we are repeatedly admonished to graduate from single-species fisheries models to multispecies or full-ecosystem models, presumably represented as computer code. That the data requirements needed to validate any such model are vastly beyond our current capacity is seen only as the result of insufficient research funding.

An alternative, and we believe much more realistic view, is that there are limitations, both practical and theoretical, to what science can accomplish (Mangel et al. 1996). Full understanding and predictability of anything as complex (and, we should add, as unobservable) as a marine ecosystem will forever remain a chimera. The implications seem obvious. Progress in fisheries management will now proceed most rapidly, not from vastly increased research effort in marine biology, but from research into ways to deal with this irreducible uncertainty, or as it might be called, unknowability. This is a topic that has hardly ever been studied in the fisheries literature, to our knowledge, so that progress might be quite rapid.

Fisheries managers (whether individuals or committees) are regularly faced with the problem of setting catch quotas on the basis of current information. They may be quite aware of the fact that this information is incomplete, so that sustainable catch levels cannot be determined with a high degree of certainty. But how are the managers to take this uncertainty into account? Should they simply ignore it and base quotas on the "best scientific estimates" currently available? Our perception is that most management decisions are made in this way—and with good reason. Any admission of uncertainty only encourages the fishing industry to demand quotas at the upper limit of the confidence interval, on the grounds that science has not "proved" that lower quotas are necessary.

This approach would perhaps be workable if the system were self correcting, in the sense that excessive quotas in one year would have immediately detectable effects on the fish population, leading to reduced quotas in the next year. The truth is that overfishing, unless it is extreme, often takes years to detect. Moderate overfishing may lower the resilience of the population, but the impending collapse cannot be predicted from the available data. Also, reductions in quotas are always politically difficult to achieve, especially given the all but universal tendency towards overcapitalization in commercial fisheries.

In addition to these biases, actual fishing mortality often greatly exceeds the targeted level, from a variety of causes including unreported catches, by-catches, discards of small fish, and incidental mortality. Moreover, the productivity of marine ecosystems may be disrupted to an unknown extent as the result of habitat damage by fishing gear, or from pollution, as well as from the capture of species that serve as food for other commercial species. Little if any of this incidental impact is quantifiable in any scientific sense.

Given all these sources of uncertainty, error, and bias, is it any wonder that valuable fish populations continue to disappear at an alarming rate? What, if anything, can be done to reverse the trend?

Biological and Economic Responses to Uncertainty: Bet Hedging

Both the world of biology and that of economics possess a variety of techniques for dealing with uncertainty. Of particular interest in the fisheries context is the use of "bet hedging" strategies in biology and economics.

Bet hedging is a form of diversification of activities, having the purpose of reducing risk through pooling or averaging of (at least partially) independent random events. In biology, various types of reproductive strategies are thought to constitute bet hedging in uncertain environments (Seger and Brockmann 1987, Yoshimura and Clark 1993). Examples include multiple episodes of reproduction (iteroparity), dispersal of progeny, and delayed germination of seeds. At the population level, metapopulation structures may increase the chances that a species will survive in spite of local extinctions (Pulliam 1988).

In the financial world, bet hedging can be observed in the common practice of portfolio diversification, and also in the purchase of accident and liability insurance. Both of these practices serve to reduce the risk of a severe loss of financial assets. Bet hedging is usually thought to involve a cost, or "premium," in terms of a decrease in expected benefits, which is accepted in order to achieve a reduction in risk.

Bet Hedging in Fisheries: Protected Marine Reserves

How can fisheries management strategies be redesigned so as to include a bet hedging component? The risk that is to be avoided, of course, is a collapse or severe decline in the fish population as a result of overfishing.

The current "world view" of fisheries management is that every commercially valuable stock should be exploited at the optimal level. Given the large uncertainties and biases of management, overfishing of every stock seems almost predetermined. This practice, clearly the opposite of bet hedging, suggests what a bet-hedging management strategy would consist of: different stocks, or substocks, would be managed in different ways.

The simplest way to diversify the management of a given fishery resource would be to exploit part of the resource while protecting the remainder. We therefore propose that Protected Marine Reserves (sometimes called Marine Protected Areas, or "no-take" areas; Shackell and Willison 1995) should become an integral component in the management of all marine fisheries. The actual design and implementation of marine reserves would depend on what is known about the biological characteristics of each particular species or species complex. For the purposes of discussion, we will here consider the case of a demersal species inhabiting a large area of the ocean floor. The design of marine reserves for highly migratory species will obviously involve additional complications.

Desirable features of a program of Protected Marine Reserves are:

1) The area included in the reserve should be large enough to protect the resource in the event of overfishing in the unprotected area. Several mathematical models (see Appendix) suggest that reserves need to include up to 50% of the original population in order to hedge successfully against overfishing.

2) The reserve area should serve as a "source" (in the sense of metapopulation theory: Pulliam 1988) capable of replenishing the exploited stock in the event of its depletion (Brown and Roughgarden 1995). In particular, reserves should protect spawning grounds and other areas critical to the viability of the population.

3) The reserve areas should be rigorously and completely protected. Typically, reserve areas will contain greater concentrations of fish than exploited areas, making them prime targets for poaching. As in terrestrial reserves, poaching must be treated as a criminal activity.

Protected marine reserves would provide benefits over and above protection of the resource. In general terms, reserves would preserve marine biodiversity by protecting intact marine ecosystems. They would also facilitate scientific research, in that the unexploited area would play the role of a control in the "experiment" of fishing (Lindeboom 1995).

Problems of Reserve Design

Many practical issues will arise in the design of marine reserves. How large should the reserve be and where should it be located? Should there be one large, or several small protected areas? Should the reserve be tailored for individual species, or for the protection of an entire marine ecosystem? Economic as well as biological aspects may influence reserve design. For example, a large reserve encompassing traditional fishing grounds may unfairly affect local fishing communities. Fragmented reserves may have fewer economic impacts, but may be less effective and more difficult to manage than one or two larger reserves. Reserves should be permanent, but this requirement will have to be balanced with the need for flexibility in reserve design. Because of the very uncertainties that underlie the need for reserves, the concept of an "optimal" reserve may be meaningless. As in other instances of bet hedging, adopting a diversified strategy is the important step; the exact allocation of total assets to different types of investment is then largely a matter of judgment.

Comparison of Protected Reserves with Other Strategies

Protected marine reserves are not at present a common component of fisheries management programs. Indeed, many fisheries biologists behave as if they consider reserves as unnecessary or unworkable. Others have asserted that reducing catch or effort levels would have the same effect as a reserve. This claim is erroneous and can only arise from a misunderstanding of the role of uncertainty and uncontrollability in fisheries management.

Opening the entire population to exploitation exposes it to the risk of depletion, even if inadvertent. While it is obviously true that this risk would be reduced with reduction of the allowable catch, the uncertainties and biases associated with setting quotas and determining actual fishing mortality imply that the fishery would probably remain vulnerable unless the quotas were set far below the "best point estimates." As noted, target fishing mortality in the Northern cod fishery should have been reduced from 0.2 to 0.1 if even a moderate degree of risk aversion were to be included. Given that actual fishing mortality often exceeded the targeted value by up to 200% (Myers et al. 1997), even this unheard-of reduction might not have been sufficient to save the cod fishery. In any event, achieving a given target fishing mortality, whether 0.2

or 0.1, has two critical prerequisites: first, stock assessments must be accurate and up-to-date, and second, all sources of fishing mortality must be accurately accounted for. As we have already noted, often neither of these prerequisites holds true.

Other management practices, such as mesh or other gear restrictions, may also reduce the risk of overfishing, but, like reductions in catch quotas, they do not amount to a diversification of management strategy, but only to a switch to an apparently more conservative strategy. The possibility of biases, errors, and excessive catch rates remains in effect under such restrictions.

An important aspect of bet hedging is that risk reduction can be achieved at minimal cost, and our models suggest that this may be true for reserves. For example, placing 50% of a population's natural marine habitat into a reserve does not necessarily imply a 50% reduction in long-term catches, particularly if the reserve is highly productive and operates as a source. Also, because of the safety aspect of the reserve, the exploited area probably can be fished somewhat more intensively than would be desirable in the absence of the reserve.

Maintenance and protection of marine reserves will incur certain costs. If successful, the reserve areas would contain higher concentrations than the exploited areas. In addition, fish inside the reserve would tend to be larger. Poaching would therefore be especially attractive in the short term. It might be argued that reserves would interfere with economic efficiency (Walters and Pearse 1995), but reducing the risk of collapse by maintaining an adequate reserve has to be weighed against the short-term gains of "creaming the top" off the reserved stocks. It is certainly clear that reserve areas would need to be rigorously policed to prevent poaching; present satellite technology would make it easy to accomplish the necessary monitoring.

A Model of Uncertain Harvests

It is probably not useful to attempt developing a general model of marine protected areas, given the great variety of marine ecosystems and conceivable management regimes. To illustrate our ideas, we model a single harvested stock that grows according to a discrete logistic (Ricker) equation. Thus, in the absence of harvest, the stock in year t, $N(t)$, and the stock in year $(t + 1)$, $N(t + 1)$ are related by:

$$N(t + 1) = N(t)\exp\left[r\left(1 - \frac{N(t)}{K}\right)\right] \quad (1)$$

where r and K have the usual interpretations. In particular, K is carrying capacity, in the sense of a stable steady state, and e^r is maximum per capita growth rate of the population. The role of a reserve is to prevent part of the stock from being harvested. In particular, we assume that a fraction A of the area in which the stock exists is available for harvesting and that the

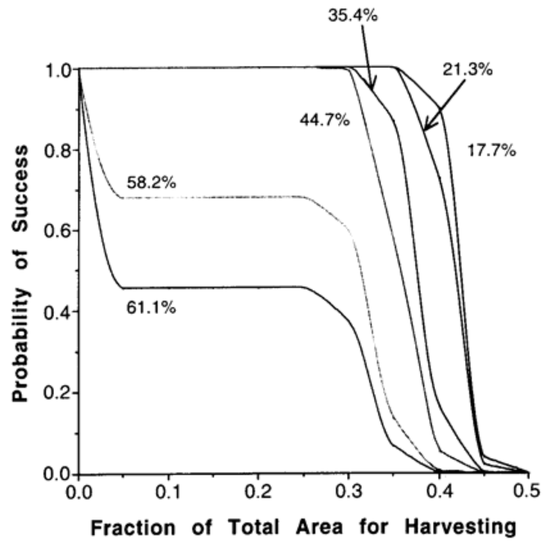

FIG. 1. The probability that the stock $[N(t)]$ remains $>0.6K$ for a 20-yr time horizon, as a function of the fraction A of area available for harvesting, for six different coefficients of variation in the harvest distribution. The model assumes that $N(1) = K$ and uses beta distributions for the harvest, all with the same mean, 0.5.

harvest fraction in this area is targeted at u. However, we assume that the target harvest is uncontrollable. This lack of controllability is captured by assuming that the harvest fraction has a probability distribution. We further assume that the mean of the distribution is fixed at the target harvest fraction, but that the actual harvest varies about this mean.

As a criterion for successful management, we assume that the stock starts at carrying capacity and consider the probability that it remains >60% of carrying capacity over a time horizon of T yr. The notion of maintaining the stock $>0.6K$—which puts it in the so-called "Optimal Sustainable Population" region—appears in legislation such as the U.S. Marine Mammal Protection Act (MMPA) of 1972 (16 U.S. Code 1361 et seq., Publ. L. 92-522, as amended) and Magnuson Fishery Management and Conservation Act (16 U.S. Code 1801 et seq., amended 104 Congress, 'Sustainable Fisheries Act').

In the Appendix, we show how the probability of successfully achieving this goal can be computed. For computations, we used $r = 0.5$ (so that this is in the non-chaotic regime of the stock dynamics), $K = 80$, and $T = 20$. We used six different frequency (beta) distributions of catch, each with a mean of 0.5 (so that half of the animals in the harvested region are captured on average) and with coefficient of variation (CV = standard deviation of the harvest fraction/mean of the harvest fraction) ranging from ~18% to ~61%.

The results (Fig. 1) are striking. Even when the CV is moderate (say, <50%), the chance of success drops

TABLE 1. Fraction (A) of the fishing ground available for harvest to ensure a given level of protection for 40 yr, and the associated expected total catch (C) (see Appendix).

Mean harvest rate†	Level of stock protection 95%		99%	
	A	C	A	C
0.5	0.304	13.12	0.271	11.82
0.4	0.367	12.71	0.347	12.11
0.3	0.472	12.30	0.443	11.62
0.2	0.686	11.93	0.634	11.14

† CV = 50%.

rapidly from 1 once the fraction of the total area available for harvesting becomes greater than ~30%. When the CV is larger, the result is even more impressive: even at very low areas available for harvest (5%), the chance of success is <1. That is, a strategy that is very conservative on average is still likely to fail if it is too difficult to control.

We also experimented with unknowable carrying capacity. Interestingly, the results are not nearly as striking, as long as the carrying capacity is not too far off. Other models (J. Roughgarden, *personal communication*) have also shown this effect.

One conceivable alternative to a reserve is simply to lower the catch level. For example, if the mean catch is 10% of the stock, with a 50% CV, then there is >99% probability of keeping the stock >0.6K for a 40-yr time horizon. The problem, of course, is that catch suffers. The methods described in the Appendix allow us to determine the size of reserve required to ensure a given level of stock protection and the catch associated with that reserve size. Typical results are shown in Table 1.

Two important points emerge from this table. First, a reserve can simultaneously lead to stock protection and a higher level of catch. For example, at a 95% level of stock protection over the 40-yr time horizon, a reserve of 70% of the potential fishing ground and a catch rate of 0.5 both protects the stock and gives an expected catch that is nearly 50% larger than the expected catch if the mean catch rate were reduced to 0.1 and the entire fishing ground fished. Second, it is possible to maximize catch while protecting the stock. For example, at a 99% level of protection, a mean catch rate of 0.4 provides slightly better expected catch than any of the alternatives.

We thus conclude that a system based on reserves may simultaneously provide protection of the stock and a higher long-term catch by allowing greater intensity of fishing in the fraction of the potential fishing ground in which fishing is allowed.

Finally, and not obvious from the figures or tables but consistent with our notions of fundamental uncertainties, the reserve provides insurance against errors in the model. That is, any real stock is managed with estimates of growth rates and carrying capacities. Furthermore, actual mean catches may exceed targeted values. A protected reserve provides a buffer against many of these uncertainties, without necessarily leading to great reductions in catch.

DISCUSSION

Widespread concern has been expressed over the failure to manage the world's ocean fisheries in a sustainable way, in spite of the opportunities provided by the 1982 Law of the Sea, and by EEZs. Recent conferences with titles such as "Re-inventing Fisheries Management" (held in Vancouver, British Columbia, Canada in February 1996) and "Ecosystem Management for Sustainable Marine Fisheries" (held in Monterey, California, USA, in 1996) attest to the desire for new approaches that would improve the dismal record. The most important component now needed is an operational admission of the limitations of science in comprehending and controlling as complex and unobservable a system as the marine environment.

Novaczek (1995) lists eight important advantages of Marine Protected Areas (MPAs). She says that MPAs can be used:

1) to protect biomass and population structure of commercial species,
2) to limit by-catch of juveniles,
3) to protect ocean biodiversity,
4) to protect essential life stages of commercial species,
5) to protect and enhance productivity,
6) to provide a location for marine research,
7) to protect artisanal and community fisheries, and
8) to enhance public education and encourage non-destructive enjoyment of the sea.

We would only add that MPAs can serve to hedge against inevitable uncertainties, errors, and biases in fisheries management. Marine Protected Areas (or as we have called them, simply, protected reserves) may well be the simplest and best approach to implementing the precautionary principle and achieving sustainability in marine fisheries.

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APPENDIX

In this appendix, we provide details for the computation of the success probability for the model of a stock growing according to the discrete logistic equation with unknowable harvest. We also clarify the assumptions used in the calculation.

Assume the size of the stock in the current year is $N(t)$. If the reserve fraction is $1 - A$, then the stock size on the reserve:

$$N_r(t) = (1 - A)N(t) \tag{A.1}$$

is untouched. The stock available for fishing is

$$N_f(t) = AN(t) \tag{A.2}$$

and a fraction u of this stock is harvested. Thus, the total stock remaining after fishing is

$$\begin{aligned} N_r(t) + (1 - u)N_f(t) &= (1 - A)N(t) + (1 - u)AN(t) \\ &= (1 - uA)N(t). \end{aligned} \tag{A.3}$$

We assume that this stock is well mixed over the combined reserve and fishing areas in order to determine the stock size in the next year. That is, the reserve boundaries are set for harvesting but the stock moves smoothly across the boundary and fills the entire fishing ground.

Define the probability of success by

$$p(n, t) = \Pr\{N(s) > n_c \text{ for } t < s \leq T \mid N(t) = n\}. \tag{A.4}$$

Here, $n_c = 0.6K$ is the critical level and T is the length of time over which we focus protection.

This function can be evaluated by a dynamic iteration equation. At $t = T$,

$$p(n, T) = \begin{cases} 1 & \text{if } n > n_c \\ 0 & \text{otherwise.} \end{cases} \tag{A.5}$$

If the stock at the start of the fishing season in year t is n, then the size of the stock at the end of the fishing season is $n_u = (1 - uA)n$ and the stock at the start of the next season will be $n_u f(n_u)$, where $f(n_u) = \exp(r(1 - n_u/K))$. Consequently,

$$p(n, t) = E_u\{p(n_u f(n_u), t + 1)\} \tag{A.6}$$

where E_u denotes the expectation over the distribution on the harvest rate.

One can also compute the total catch this way by defining

$$c(n, t) = E_u\left\{\sum_{s=t}^{T-1} u(s)AN(s)\right\} \tag{A.7}$$

so that $c(n, T) = 0$ and

$$\begin{aligned} c(n, t) &= E_u\{Aun + c(n_u f(n_u), t + 1)\} \\ &= A\bar{u}n + E_u\{c(n_u f(n_u), t + 1)\}. \end{aligned} \tag{A.8}$$

We assume that the harvest fraction u follows the beta density (Martz and Waller 1982)

$$g(u) = c_n u^{\alpha-1}(1 - u)^{\beta-1} \tag{A.9}$$

where c_n is a normalization constant (which can be written in terms of gamma functions) and α and β are parameters. For the density of Eq. A.9, the mean and square of the coefficient of variation of u are:

$$\begin{aligned} \bar{u} &= \frac{\alpha}{\alpha + \beta} \\ \mathrm{CV}^2 &= \frac{\beta}{\alpha(\alpha + \beta + 1)}. \end{aligned} \tag{A.10}$$

Thus, one can specify the mean and coefficient of variation of u and determine the values of α and β by solving Eq. 11.