MARINE RESERVES FOR FISHERIES MANAGEMENT: WHY NOT

RICHARD PARRISH
Pacific Fisheries Environmental Laboratory
National Marine Fisheries Service
1352 Lighthouse Avenue
Pacific Grove, California 93950
parrish@pfeg.noaa.gov

ABSTRACT

Marine reserves have recently become a politically correct way of viewing the management of marine resources. Much of the reason for this is due to the depressed state of many of the populations that have been the mainstay of both commercial and recreational marine fisheries. The apparent failure of past management has led to a headlong rush for a paradigm shift. Marine reserves that occupy no more than about 5% of the productive habitat can provide sites for research, for monitoring natural variability, and for preserving habitat and diversity for heritage purposes.

But the case for large marine reserves for fisheries management purposes has not yet been adequately made. The few available modeling studies suggest that for fisheries management purposes, marine reserves need to be on the order of 50% of the productive habitat. Analyses presented here suggest that, with reserves this large, current yields can be obtained only with a considerable increase in total fishing effort and a very large increase in the mortality rates in areas open to fishing. This implies a large increase in the trawling rate, and probably associated ecological damage, in the exploited area. Even if it were desirable to manage an individual species with large marine reserves, the concept breaks down when applied to the West Coast trawl fishery, which is based on many species, each with a different habitat. A marine reserve established for overexploited groundfish provides little real protection for migratory species such as Pacific hake, but may greatly increase the cost of fishing for these species.

INTRODUCTION

There is a sea change brewing in the way we manage our fishery resources in the California Current region, and it has its origin in the last several decades of decreasing yields and populations of many of the most important West Coast sport and commercial fisheries (Ralston 1998). It is not yet clear what changes will occur, because there are several competing strategies as to how we should alter current management. However, marine reserves are certain to play a much more important role than they have in the past, and a wide range of sizes has been suggested (Yoklavich 1998). Although no-take marine reserves have played a very minor role in the management of marine fisheries of the California Current region, areas have been extensively closed to specific commercial gear types (gill nets, purse seines, and trawl nets). For the purposes of this work I will define *marine reserves* as areas in which fish and shellfish cannot be legally taken by either commercial or recreational fishers, and *closed areas* as areas where specific fishing gear cannot be used.

The specifics of size and siting of marine reserves will be topics for research, confrontation, and political action in the coming years. For the purpose of this paper, I will use the classification developed by a working group at a recent workshop that suggested marine reserves could be classified into three design types based upon the motivations for establishing the reserves (Yoklavich 1998). These types are marine reserves as heritage sites and areas for fishery research, marine reserves as a buffer or insurance against overfishing, and marine reserves as an alternative strategy for sustainable fisheries. The working group suggested that the percentages of the total habitat, or range of an individual species, which was necessary to fulfill the goals of these types were <5%, 5%–20%, and 20%–50%, respectively.

The smallest reserves, those primarily intended for heritage and research purposes, are relatively uncontroversial. It is difficult to imagine that any resource users would be against the concept of reserves of this size, unless of course the reserves were in "their fishing hole." I will simply state that, in my opinion, reserves of this kind are long overdue, and managers should quickly proceed to develop them in all major habitat types.

The middle case, the use of reserves as a buffer or insurance against overfishing, will not be directly addressed in the analyses presented here. Analyses of this case should include multispecies effects and economic effects on fisheries, which are beyond the simple analyses presented here.

The largest reserve class—an alternative strategy for sustainable development—may be viewed as a form of adaptive management; i.e., a major alteration in management strategy followed by an evaluation of this alteration, rather than a gradual evolution of the management strategy. People favoring this size of reserve range from those who believe that incremental adjustments to the present management system cannot be expected to correct the present downward trends of many of our valuable marine resources, to those with a philosophical opposition to fishing and an acceptance of large reserves as a partial solution.

The purpose of this paper is to assess the population dynamics that would most likely result if adaptive management utilizing harvest refugia in 20%–50% of total habitat were enacted. In particular, I will compare the management potential of large marine reserves with the management strategy that has been followed by the Pacific Fisheries Management Council (PFMC).

BACKGROUND

One of the major difficulties confronting fishery research and management is in separating the effects of fishing from the effects of environmental variation at decadal or longer time scales. It is clear that at least parts of the California Current system have been very unproductive for an extended period, for both zooplankton (Brodeur and Ware 1992; McGowan et al. 1998) and fishes (Hollowed and Wooster 1992; Beamish and Bouillon 1993; Francis and Hare 1994). If marine reserves had been in place over the last several decades, it would be possible to determine whether the density of fishes within the reserves had declined, and, if so, how much in comparison to areas where exploitation has occurred. The use of marine reserves as controls to evaluate the effects of extensive and varied exploitation of living marine resources appears to be an essential tool in the research that will be necessary to tease out the complicated interactions between natural and human-induced alterations of these resources.

It should be noted that the analyses presented here are based on quite simple population dynamics; I have largely ignored multiyear to regime-scale environmental variation, which I believe is one of the most important factors in the current fisheries' situation.

Fish Behavior and Marine Reserves

One of the common arguments used by people favoring marine reserves is that they will provide areas where the marine fauna can recover to densities approaching those prior to exploitation. It is clear from population dynamics theory that marine reserves will foster conditions within the reserves that will result in increased fish density and diversity and a more natural age composition in comparison to that occurring at the present highly exploited state. But the state that is fostered will not be the same as that before exploitation. There will be fewer pelagic predators and small pelagic forage fishes, because of their exploitation outside the reserves, and there may possibly be more benthic and sedentary fishes. Because fishing effort will be displaced from areas that are included in reserves, the areas open to fishing should be expected to have exploitation rates considerably higher than the present ones. Marine reserves may increase recruitment to exploited areas for species with extensive pelagic larval stages, but species with little dispersal during the larval stage are unlikely to increase outside the reserves.

TABLE 1
Fish Behavior and Mobility in Relation to Residence Time within a Marine Reserve

1. Epipelagic and migratory species
Species that freely move in and out of reserves; they are often stocks with a large biomass. Their fisheries have minor bycatch, a minor effect on the substrate, and a high percentage of the catch may be taken in a relatively minor portion of their range:

Hake	Salmon	Albacore
Herring	Squid	Mackerels
Sardine	Anchovy	White seabass

Marine reserves will do little toward achieving optimum yield for these species. Annual quotas, closed seasons, or limitations on total and/or temporal effort will more likely be successful.

2. Benthopelagic, often schooling species
Species with moderate movement in and out of reserves and extensive larval dispersal:

Bocaccio	Widow rockfish	Pacific ocean perch
Chilipepper	Sablefish	Shortbelly rockfish
Kelp bass	Lingcod	Yellowtail rockfish

These are the most likely candidates for primary management by marine reserves or closed areas. Fisheries often have high bycatch rates and effects on the substrate.

3. Benthic, sedentary species
(particularly species such as abalone that have little larval dispersal); species that would have little movement out of reserves:

Many flatfishes	Abalones	Many littoral species
Many rockfishes	Sea urchins	Market crab

These are good candidates for achieving near virgin biomass levels in reserves but not likely candidates for improvement of fishery yields through reserve or closed-area management.

The success of marine reserves in maintaining near virgin densities will be highly dependent upon the behavior of the individual species (table 1). Species with highly pelagic or migratory behavior, such as Pacific sardine or Pacific hake, will be only partially, temporally protected by reserves, and their densities within the reserves should not be expected to differ greatly from those outside the reserves. Species with moderate mobility will be partially protected by reserves; depending on how much they move, their densities in the middle of large reserves could approach virgin densities. Near reserve boundaries, their densities will approach those outside the reserves. If, however, fishers respond to a reserve by concentrating their activity just outside the reserve, the net effect near the boundary may be densities that are considerably less than those deep in the reserve or even those at a considerable distance from a reserve.

Modeling studies suggest that marine reserves are most likely to positively affect fishery yields in species with moderate movements (Polacheck 1990; DeMartini 1993). This is particularly true when the reserve protects the younger fish that will move into the area open to fishing as they become larger. This was obviously realized by those who closed nearshore areas to trawling and have thus protected nursery grounds for more than four decades in California.

Benthic, sedentary species that move in and out of a reserve very little as adults are most likely to reach biomass densities and age structures near virgin levels. In theory, these species could attain even higher densities within marine reserves than before exploitation. This could happen if their populations are limited by predators or competitors that have highly or moderately mobile behavior, because these species would tend to be less dense than before exploitation. In contrast, modeling studies suggest that sedentary species are unlikely to increase with marine reserves (Polacheck 1990; DeMartini 1993). In fact, it is unlikely that a species could achieve near virgin biomass levels within a reserve and also increase fishery yields above levels that would occur with proper management without reserves. The exception to this is the special case where a large percentage of the recruitment of a stock consistently comes from a relatively small percentage of its habitat, and this same habitat is placed in a reserve. Species such as market squid and Pacific herring, which reproduce in restricted spawning grounds, are examples; in both cases, however, the species are highly mobile, and current fisheries are located primarily on their spawning grounds.

Growth versus Recruitment Overfishing

Fisheries biologists generally divide overfishing into two conceptual classes: growth overfishing and recruitment overfishing. The management techniques used to avoid these two classes of overfishing are quite different.

Growth overfishing is most likely to occur in species with low growth and natural mortality rates as well as delayed sexual maturity. It is therefore likely to occur in fisheries for rockfishes and other slow-growing groundfish species. Generally, the term refers to fishing a stock beyond the maximum yield per recruit, and this generally occurs when a species is exploited before the age that an individual cohort achieves its natural maximum biomass.

Growth overfishing is generally avoided by delaying, or at least reducing, fishing mortality on fish that have not yet reached the size or age of sexual maturity; this is often near the age that a year class reaches its maximum biomass. Typical management measures to avoid growth overfishing include size restrictions, mesh size restrictions, and area closures to prevent harvest in nearshore nursery grounds. These area closures have traditionally been limited to specific types of fishing gear (e.g., trawls or purse seines). No-take reserves have not been used to prevent growth overfishing in the California Current region.

Depending on the growth and behavior of individual species, reserves may or may not affect growth overfishing. Nonetheless, many of the beneficial effects of marine reserves observed in modeling studies are related to growth overfishing. The reserve models essentially protect fish at younger ages; then these fish move out of the reserve and are caught at a beneficial yield-per-recruit age and mortality rate. If reserves were concentrated in nearshore, nursery areas, they would have the same effect as the gear-specific closed areas mentioned above. In this case, the reserves will not fulfill the role of maintaining near virgin densities and population age structures because they will not protect adults. For sedentary fishes, where the areas open to fishing encompass the habitat of the whole age structure of the species (i.e., where there is no nursery grounds effect), regulations to prevent growth overfishing will have to be maintained.

Recruitment overfishing refers to fishing that reduces reproductive output to levels that markedly decrease recruitment. It is generally assumed that this does not occur at biomass levels less than 50% of the virgin level. Management techniques to avoid recruitment overfishing include setting annual quotas, fishing mortality, or fleet sizes at levels that will not reduce the adult biomass below some reference level. Unfortunately, this reference level is difficult to determine, and in practice it is seldom established until it has been exceeded.

Marine reserves of even modest size may help prevent recruitment overfishing of fishes that are sedentary, or have limited mobility and long pelagic larval stages. Very large marine reserves may protect enough of these fishes to prevent recruitment overfishing by providing a source of young fish even without any other regulations. In fact, several models suggest that reserves occupying up to 50% of a species' habitat may even increase yields (Polacheck 1990; DeMartini 1993). DeMartini (1993) showed that increased yields and protection of spawning biomass were highly dependent upon the behavior and growth rates of the species modeled; the best fishery and spawning enhancement occurred in species with moderate mobility and fast growth rates.

Spawner-Recruit Relationships

One convention often used in fisheries assessments is to assume that natural mortality and growth rates are not dependent on year or year class. Given these two assumptions, the shape of the spawner-recruit relationship becomes the primary factor in determining the stock's surplus production and thus the productivity of the stock. The spawner-recruit model most often used for California Current species is the Ricker model:

$$R = a\,S\,e^{-b\,S}$$

where R = recruit biomass or number
S = parent biomass, number, or reproductive output
a = the density-independent parameter
b = the density-dependent parameter

The potential productivity of a species with a Ricker spawner-recruit relation is described by the *a* coefficient, whereas the effect of stock size in reducing the potential productivity is determined by the *b* coefficient. Although it is not generally realized, the *b* coefficient also determines the percentage of the equilibrium stock size at which the maximum surplus production occurs. When biomass is expressed as a percentage of the equilibrium biomass, there is a unique *b* coefficient that defines any stock that has optimum production at a given percentage of equilibrium biomass (although it may be scaled by the assumed age at recruitment and the units that are used).

Ricker spawner-recruit models are usually fitted with a linear regression of the log of recruits/spawner on reproductive output or some proxy such as spawning biomass. A Ricker spawner-recruit relationship with maximum surplus production at 35% of the virgin biomass has a moderate dome shape (fig. 1); with maximum surplus production at 40%, the relationship has only a slight dome; and with 45%, recruitment continues to increase even beyond the virgin biomass level. In each case the potential productivity is dependent upon the *a* coefficient.

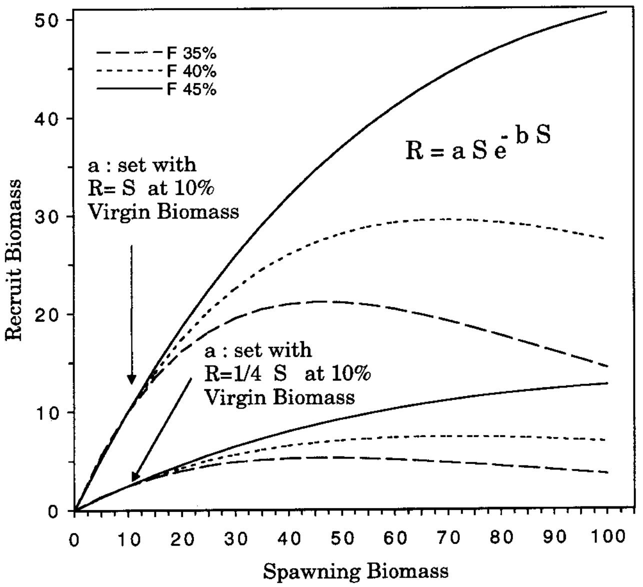

Figure 1. Ricker spawner-recruit curves. The upper set has an *a* coefficient four times as large as the lower set.

Source of Density-Dependence in Recruitment

The magnitude of compensatory density-dependence (the tendency for increased recruitment rates as the parent biomass decreases) is a measure of a stock's resiliency to exploitation and to temporary adverse environmental conditions. The source and degree of this density-dependence is not known for most, or perhaps any, of the exploited marine fishes in the California Current system. Knowledge of the source, or at least the life-history stage at which most of the density-dependence occurs, will be crucial in determining the relative merits of reserve versus traditional management.

Density-dependence in recruitment could occur during three life-history stages. The first stage includes processes affecting the production of eggs or larvae, and it would most likely be related to the availability of food for mature and maturing fish. Variations in food availability and quality would be expected to affect both the number and quality of eggs or larvae produced. This may be particularly important for live-bearers such as the rockfishes and for indeterminate spawners such as the California sardine.

The second life-history stage—the pelagic larval phase—is quite extended in many California Current groundfish species. Most of these species have relatively small adult populations and therefore a very small biomass at the pelagic larval stage. Density-dependence at this stage is therefore unlikely because the larvae constitute a very minor portion of the zooplankton. Possible exceptions to this are Pacific hake and shortbelly rockfish, which have large populations; one could also argue that these species are not really groundfish but benthopelagic species.

The third life-history stage—postsettlement juvenile—is a likely candidate for density-dependence in many benthic fishes because their nursery grounds are often spatially restricted, so predation, competition, and cannibalism are potential sources of density-dependence in both juvenile growth and mortality. At this stage the density-dependence could be caused by the abundance of larvae or juveniles that are settling or by the abundance of older fish already present.

If a stock has an extensive larval-drift stage and if density-dependence occurs at the postsettlement stage, management with large reserves could be a real advantage for recruitment. For example, if the stock has maximum recruitment at 35% of the virgin biomass, well-placed large reserves would help maintain the stock near the level that produces the maximum recruitment even if the stock were depressed in areas open to fishing.

In contrast, if density-dependence occurs at the egg/larvae production stage (i.e., it is dependent upon the

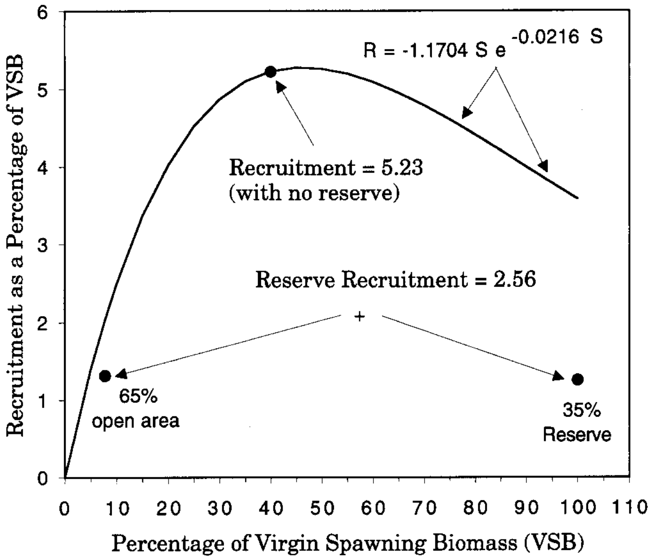

Figure 2. A comparison of recruitment under 35% reserve and no reserve management, when recruitment is density-dependent at the larval production stage.

condition of adults), management with 35% reserves could be counterproductive. To demonstrate this potential problem, I will use an example of a highly sedentary species with essentially no movement as adults between the reserve and exploited areas but with extensive dispersal during the pelagic larval stage. The stock has 40% of its virgin biomass—35% within reserves and 5% in open areas. The fish in the reserves would have a local density equal to the virgin state, and those in the open areas would have a local density of 5/65 virgin density. The stock-recruitment model is a typical Ricker spawner-recruit relation that produces a recruit biomass that is one-fourth of the spawning biomass at 10% of the virgin spawning biomass level, and maximum recruitment occurs at 35% of the virgin biomass. With reserve management, the total recruitment would be less than half of that which would occur without reserve management, and there would be more recruitment from the 5% of virgin biomass located outside the reserve than from the 35% within the reserve (fig. 2).

CASE HISTORIES

To evaluate the relative merits of reserve versus traditional fisheries management, one should first describe the state of traditional management. I will use one case that could be described as a failure (bocaccio, *Sebastes paucispinus*) and one that could be described as a success (widow rockfish, *Sebastes entomelas*).

The general harvest policy for most of the groundfish stocks regulated by the PFMC was an F35% policy (i.e., the stock should be harvested at a rate that produces a spawning potential per recruit equal to 35% of that which would occur if the stock were unexploited). Very recently, the PFMC has begun moving away from this policy—to F40% and F45% for several groundfish stocks, and it has enacted a management strategy for Pacific sardine, a very significant forage fish, that results in an average F65%.

Much of the analysis presented here will use the F35% base management strategy to compare traditional fisheries management as it has been practiced in the groundfish fisheries of the U.S. west coast, with reserve management using the management strategies that have been recently proposed to the fisheries management councils. Note that, by definition, an F35% policy will result in a steady state spawning biomass that is 35% of the virgin spawning biomass.

Given three assumptions—(1) a steady state environment, (2) a reserve system that protects 35% of the species' adult habitat, and (3) a highly sedentary species that is uniformly distributed over its habitat and highly dispersed during its pelagic larval stage—it would be expected that the reserve would prevent the reproductive output from falling below 35% of the virgin level even if the adult biomass in the area outside the reserve is reduced to trace levels. Thus in the worst case scenario a 35% reserve policy and no other fishery regulations could be considered the equivalent of a successful F35% exploitation policy with no reserves.

To assess the relative value of the historical fisheries management strategy versus reserve management, I will use the information available from stock-synthesis models for the two species: bocaccio (Ralston et al. 1996) and widow rockfish (Ralston and Pearson 1997). Bocaccio is a relatively productive species with a fast growth rate and a relatively early age of sexual maturity. It has been extensively exploited with a wide variety of gears for more than 80 years (Phillips 1939); its present biomass is in a very depressed state; and current management allows only a very small quota (Ralston et al. 1996). Widow rockfish is a less productive species, virtually unexploited by U.S. fisheries prior to 1977, when a fishery using midwater trawls rapidly developed. Landings increased quickly to a peak of nearly 28,995 MT in 1981; quotas were enacted in 1989; and the fishery has been managed with increasingly smaller quotas since 1989 (Ralston and Pearson 1997). Management was based on an F35% strategy, but this has recently been altered to F45% (PFMC 1998).

Ricker spawner-recruit curves were fitted for bocaccio and widow rockfish, and for comparison I have also shown two assumed spawner-recruit relationships. These assumed relations have an *a* coefficient that produces recruitment equal to 1/4 of the spawning when the spawning biomass is at 1/10 of the virgin level, and *b* coefficients that yield surplus production at 35% and 45% of the virgin biomass.

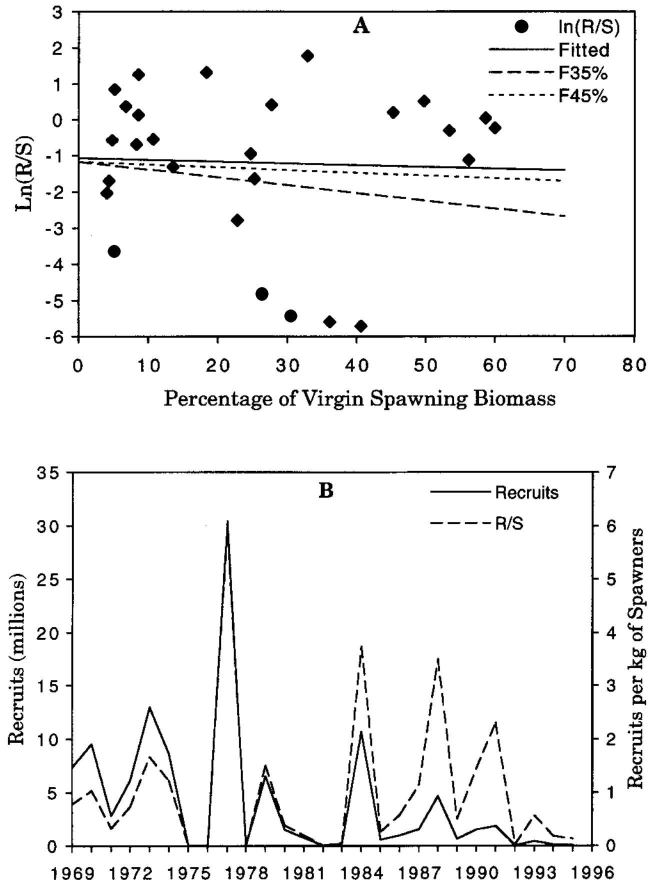

Figure 3. *A*, Bocaccio recruitment success, Ln(R/S), versus percentage of virgin spawning biomass. *B*, Bocaccio recruitment pattern 1969–95. (Data from Ralston et al. 1996.)

The variation in reproductive success of the bocaccio stock is so large that it is difficult to determine if there is any density-dependence in the relationship. The fitted Ricker relation has a maximum surplus production at F47%; however, the relation accounted for only 0.2% of the variance and was obviously not statistically significant (fig. 3A). The F35% Ricker curve has essentially the same poor fit to the data as an F45% curve or the fitted curve. The time series of reproductive success and recruitment implies that the stock is maintained primarily by infrequent years of high reproductive success (fig. 3B). This pattern suggests that recruitment in bocaccio is environment-dependent, highly variable, and that no management strategy is likely to stabilize the population.

Widow rockfish have a much narrower range of reproductive success, and there is a marked density-dependence, with the number of recruits per spawning output increasing as the stock declines (fig. 4A). The fitted Ricker relation for widow rockfish results in an F40% surplus production, which accounts for 35.7% of the variance and is significant at the $P = 0.001$ level. The time series of reproductive success also clearly shows that recruits per reproductive output increased in recent years as the biomass declined, demonstrating that widow rockfish have considerable density-dependence in recruitment (fig. 4B).

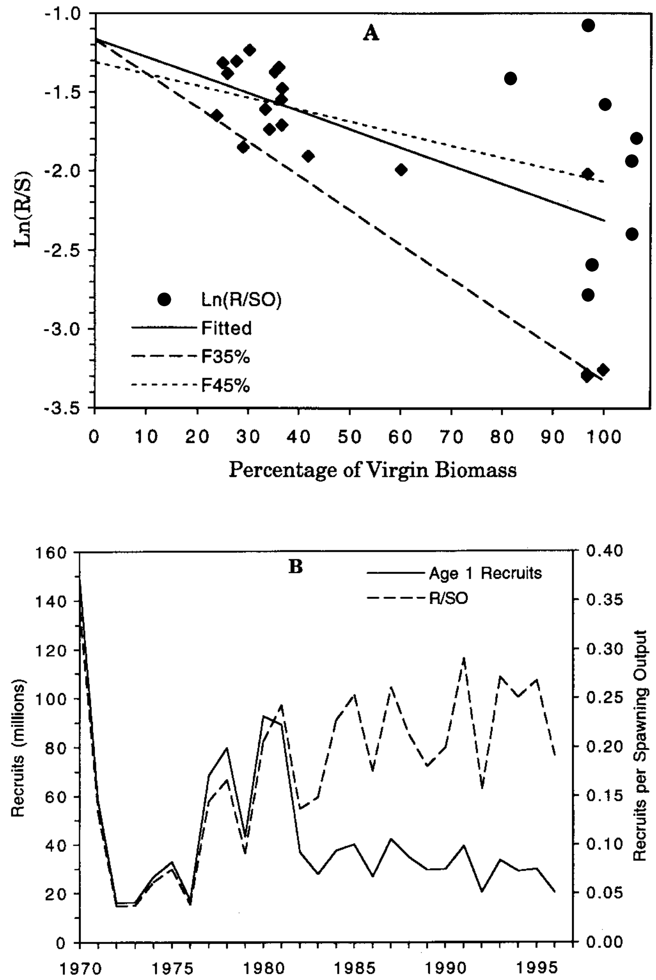

Figure 4. *A*, Widow rockfish Ln(recruits/spawning output). *B*, Widow rockfish recruitment pattern 1970–96. (Data from Ralston and Pearson 1997.)

The above spawner-recruit relationships suggest that recruitment is so variable that it cannot be determined which F strategy should be used for bocaccio, and that an F40%, not an F35%, strategy would be the minimum appropriate for widow rockfish. In 1997 an F40% management strategy for widow rockfish was proposed to the PFMC (Ralston and Pearson 1997) and in 1998 an F45% policy was enacted (PFMC 1998). It should be noted, however, that the previously mentioned and well documented climatic shift that occurred in 1976–77 could be responsible for the increase in the recruitment rate in widow rockfish as well as the lack of density-dependence in bocaccio.

Surplus Production

The potential productivity of the two species can be roughly estimated by calculating the surplus produc-

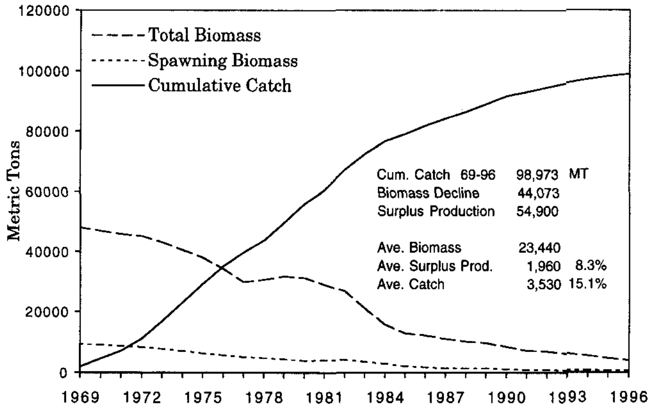

Figure 5. Bocaccio rockfish biomass, cumulative catch, and surplus production, 1969–96 (data from Ralston et al. 1996).

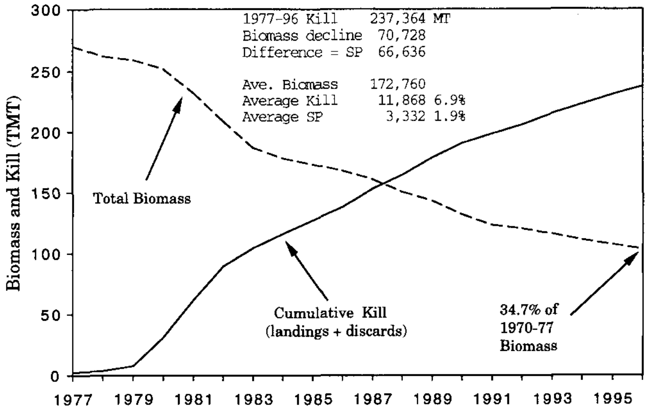

Figure 6. Widow rockfish biomass, cumulative kill, and production (data from Ralston and Pearson 1997).

tion during the period for which there is adequate information for each species. Of course, when estimated over a wide range of stock sizes, the estimate will be less than the maximum surplus production.

Although the bocaccio fishery extends back into the early part of the century, biomass estimates are available only since 1969, when the stock stood at 47,930 MT; by 1996 the stock had declined to 3,857 MT, and the cumulative catch (1969–96) was 98,973 MT (fig. 5). The 1969–96 biomass decline was 44,073 MT which, when subtracted from the cumulative catch, implies that the total surplus production over the 28-year period was 54,900 MT. Average catch over the period was 3,530 MT per year, and the average annual surplus production was only 1,960 MT. The bocaccio stock was therefore exploited at nearly twice the rate (E = 15.1%) of its average surplus production (E = 8.3%).

Widow rockfish presents a rather unusual case, because a data-based estimate of virgin biomass is available. This is because the behavior of the species made it unsusceptible to capture with traditional bottom trawls, and its deep distribution made it relatively unavailable to hook and line fisheries. The widow rockfish's average total biomass, just prior to the development of the fishery (1970–77), was 287,025 MT (Ralston and Pearson 1997). By 1997 total biomass had been fished down to 99,576 MT, 34.7% of the 1970–77 "virgin" biomass (fig. 6).

Because the stated objectives of the PFMC were to achieve an F35% management policy, the widow rockfish fishery could be termed "perfect management" in 1997, if the criterion was biomass. That is, the council would have met its target. Whether the target was right is another matter. The criterion of spawning output produces a different story. Average spawning output as calculated by Ralston and Pearson (1997) fell from an average of 442,484 (units not given) for the "virgin" population to 102,879 in 1997—23.2% of the virgin spawning output. On the basis of spawning output, it appears that the council's management strategy did not prevent the resource from declining below the stated goal.

In terms of surplus production, the widow rockfish stock had an average annual kill (landings + discards) of 11,868 MT, but an average annual surplus production of only 3,332 MT. Annual removals were 3.6 times the annual surplus production. It is expected that this ratio would be high because the data include the period when the biomass was near the virgin level; however, this is clearly the reason that the biomass dropped so quickly.

Comparison of F35% versus 35% Reserve Policies for Widow Rockfish

To directly compare the current F35% harvest policy with a management policy based primarily on reserves, I will use widow rockfish and a management situation with 35% of the species habitat being placed in reserves. According to Ralston and Pearson (1997) the 1999 catch (landings + discards) from an F35% widow rockfish fishery would be 5,689 MT with an exploitation rate of 12.6% of the summary (i.e., exploitable) biomass. Using this information, one can compare the exploitation, fishing mortality, and effort rates that would occur with the F35% management strategy versus a strategy in which marine reserves occupying 35% of the widow rockfish habitat were established.

For this comparison I will use the 1999 information to demonstrate the exploitation, trawling rates, and total effort that would be required to achieve the 1999 catch with current management versus that necessary if 35% of the widow rockfish habitat were in a marine reserve. If a reserve had been established at the beginning of the 1999 season, 65% of the exploitable biomass would have been in the area open to fishing (assuming a uniform distribution). However, as time progressed, a smaller and smaller proportion of the exploitable biomass would be outside the reserve area. Therefore, for a broader comparison I have included situations with the same 1999 bio-

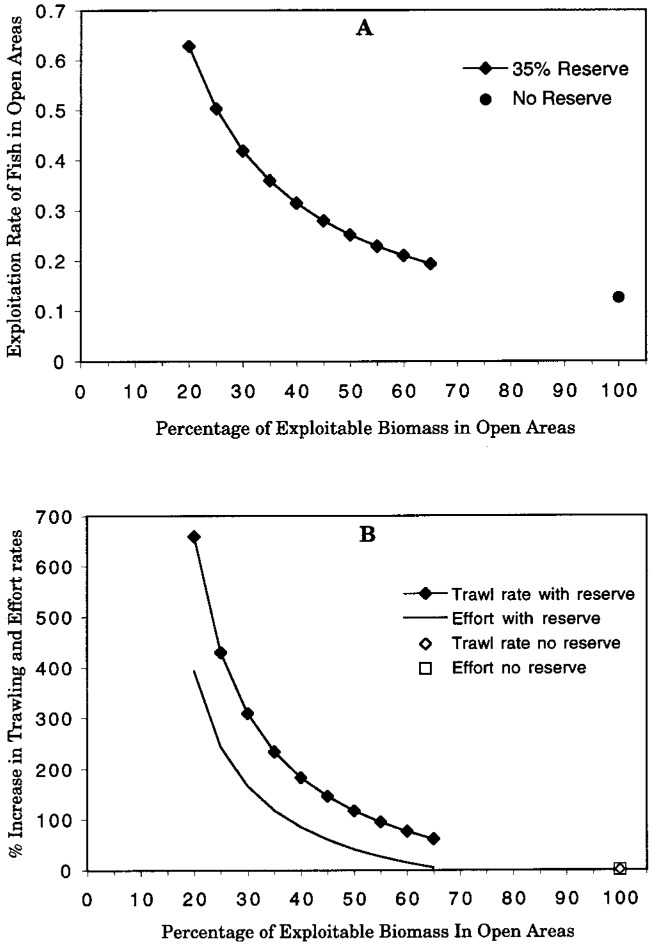

Figure 7. *A*, Exploitation rate of widow rockfish (outside of reserves) with a management of F35% and with 35% marine reserves. *B*, Widow rockfish trawling rate (in areas open to fishing) and total effort increases with F35% and with 35% marine reserves.

mass and catch, but with a varying percentage (20%–65%) of the exploitable biomass in the area open to fishing. Note that with a virgin density within the reserve and an exploitable biomass of 35% of virgin density, there would be 0% of the biomass in the area open to fishing.

In the situation where the local density of widow rockfish is the same in the reserve and in the open area, the exploitation rate of fish in the open area would increase from 12.6% to 19.3% (fig. 7A). There would be a 4% increase in total effort and a 60% increase in the trawling rate in the area open to fishing (fig. 7B). Where 50% of the biomass is in the area open to fishing, the exploitation rate is 25.1%, and the total effort and trawling rate increases are 41% and 116%. With 25% of the biomass in the open area, the values increase to 0.503%, 244%, and 429%.

An additional problem is that the increased exploitation rates on the exploited segment of the stock will reduce the age structure in the area open to fishing to just a few year classes, causing the fishery to become heavily dependent upon recruitment, which may be highly variable (figs. 3B, 4B).

The ecological damage caused by fishing (trawling or other gear) is a function of the fishing rates in an area (i.e., the instantaneous fishing mortality). Reserve management will greatly increase these rates in the area open to fishing, and decrease them to near zero within the reserve. The fishers' economic cost of harvesting is a function of the increased effort that will be required to catch the same volume of fish. The exploitation rate that the stock can support in the area open to fishing may, or may not, be higher than the current rate.

It is impossible, with this simple simulation, to determine if ecological factors (side effects of the increased trawling rate); fishery economics (the decreased catch per unit of effort); or population dynamics (increased exploitation rate) will be the limiting factor in reserve management of this type.

TRANSITION TO RESERVE MANAGEMENT

If very large marine reserves are established as an adaptive strategy for fishery management, one consideration will have to be the transition from the present state to a future state where there are near virgin levels within the reserves. At present some stocks are approaching or below 10% of their virgin levels (Ralston 1998). How long will this transition take, and what fishery yields can be taken from these depressed stocks during the transition?

In the California Current there have been three species (Pacific mackerel, Pacific sardine, and Pacific ocean perch) that were fished down to levels at which the directed fishery was closed long enough to expect a recovery of the population. The Pacific mackerel total biomass declined from a peak of 0.438 MMT in 1933 to 0.0001 MMT in 1968, and the commercial fishery was closed in 1970 (Parrish and MacCall 1978). By the late 1970s the population showed signs of a very strong recovery; in 1977 the fishery was reopened with modest quotas; by 1982, the population had surged to 1.18 MMT; and it has since declined again to 0.12 MMT in 1998 (Yaremko et al. 1999).

The Pacific sardine stock showed a similar pattern. Its total biomass was just under 4 MMT in 1934; it declined to 0.003 MMT in 1965; and the directed fishery was stopped in 1970 (Murphy 1966; MacCall 1979). Sardine biomass clearly increased during the 1980s and into the 1990s; total biomass reached 0.1 MMT in 1989 and 0.5 MMT in 1995 (Hill et al. 1998).

The Pacific ocean perch population was about 0.1 MMT before the foreign fishery developed in the mid-1960s; it declined to about 0.02 MMT in the mid-1970s and to about 0.01 MMT in 1995 (Ianelli and Zimmerman 1998). The fishery has been regulated at a lightly fished level (F = 0.05–0.10) from 1980 to the present.

Mackerel remained below 10% of the early peak biomass from 1966 to 1978. Sardine remained below 10% of the early peak biomass from 1951 to 1993. Pacific ocean perch continued to decline from about 25% of the early peak biomass in the mid-1970s to about 10% in 1995.

These examples indicate that quick-maturing, productive stocks such as the mackerel and sardine can be expected to show significant recovery in 1–3 decades when there is no directed fishery during early recovery. Slow-maturing, less productive stocks such as Pacific ocean perch may not recover in 3 decades, and may even decline further, when lightly exploited.

ALTERNATIVE STRATEGIES FOR MANAGEMENT

In recent years the management strategy used by the PFMC for rockfishes was based on the concept of a constant F35% harvest rate. This management strategy was not successful at stabilizing many of the rockfish stocks at or even near 35% of their virgin spawning biomass levels. There appear to be three major alternatives for change, and all three are currently being actively evaluated:

1. Incremental increases from F35% to F40% and higher; some of this change has already been made.
2. Establishment of marine reserves.
3. Adoption of recently proposed control rules that reduce the exploitation rate as biomass falls below some reference level. This change is also currently in progress.

As indicated by the preceding examples, catching the same quantity of fish while implementing reserve management will require an increase in total fishing effort and a large increase in fishing mortality rates within the exploited areas. Current management of widow rockfish is based on an F40% policy, and the fishing mortality required to achieve this policy without reserves is F = 0.153 (Ralston and Pearson 1997). To achieve the same landings with a reserve, the fishing mortality and fishing effort increase rapidly as the stock falls away from the virgin biomass. With a 35% reserve and a virgin stock, the fishing mortality rate required to achieve the F40% catch from the 65% open area is F = 0.2354. At a stock size 70% of the virgin biomass (i.e., with 35% in the reserve and 35% in the exploited area), it rises to F = 0.4371; at 45% it rises to more than 10 times the F = 0.153 (fig. 8). This estimate is based on the assumption that the reserve area remains at virgin biomass levels while the area outside the reserve is fished down (i.e., fish do not exchange between the reserve and open areas once they are old enough to be taken in the fishery). In addition, the entire increase in fishing effort will occur in the areas outside the reserve. If trawling does alter the nonexploited benthic fauna, the areas outside the reserves will be much more affected under reserve management than with the other two alternatives.

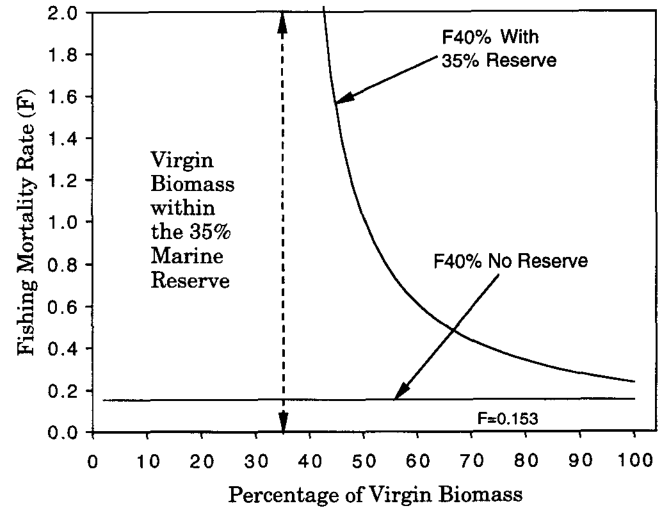

Figure 8. Widow rockfish fishing mortality rates in areas fished with and without a 35% reserve under a 40% harvest rate.

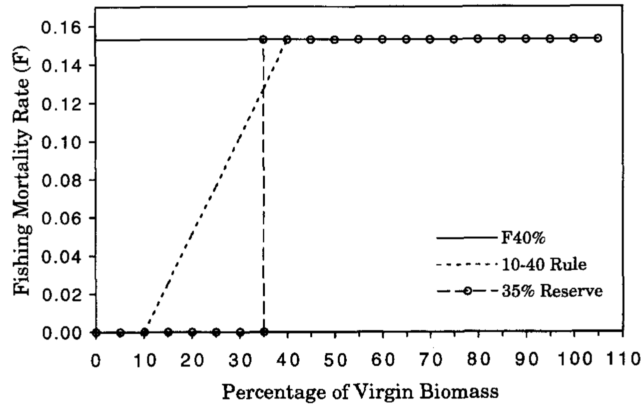

Figure 9. Widow rockfish instantaneous fishing mortality rates under different management strategies.

The third alternative for modification of the way the PFMC has been managing the Pacific Coast groundfish stocks is to base the exploitation rate on stock size and reduce the exploitation rate as the stock declines. An early example of this type of control was developed for the California Pacific mackerel fishery (Parrish and MacCall 1978). The PFMC has recently adopted such a rule for Pacific sardine, and in 1998 it adopted a new precautionary policy, the so-called 10-40 rule for groundfish management (PFMC 1998). This rule sets optimum yield at F_{MSY} when the stock biomass is above 40% of the virgin biomass, and the optimum yield declines linearly from F_{MSY} at 40% of the virgin biomass to zero at 10% of the virgin biomass (fig. 9).

The crisis in fishery management for groundfish and salmon in the region managed by the PFMC leads me to believe that all three alternatives will be employed during the next decade.

CONCLUSIONS

The admittedly "quick and dirty" fisheries analyses presented here suggest that considerable research should be carried out before very large reserves are considered as a viable alternative for managing the major fishery stocks of the California Current region. Concerns about management with large marine reserves include:

1. Considerable increases in fishing effort will be required to catch the same volume of fish, and the larger the reserves, the larger the increases will have to be.
2. Fishing mortality rates in the areas open to fishing are likely to increase well above present rates; if trawling causes ecological damage, reserves will extend this damage in the area open to fishing.
3. Reserves will have undesirable effects on the economics of fisheries for migratory species that are managed by annual quotas. These economic problems could be avoided by instituting closed areas for the fishing gear used to catch the species that need protection.
4. Depending upon the source of density-dependence in recruitment, reserves may result in considerable decreases in recruitment.
5. Increased exploitation rates in areas open to fishing will greatly reduce the age structure of the exploited portion of the population, concentrating most of the biomass in a very few year classes. Since many species (e.g., bocaccio) have highly variable recruitment, annual landings would also be expected to become more variable.
6. Some of the above concerns could be reduced if the total take were reduced by a percentage equivalent to the percentage of the habitat that is placed in reserves.

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