Abstract—Shortraker and rougheye rockfish (*Sebastes borealis* and *S. aleutianus*) have been an independent management subgroup of the Gulf of Alaska slope rockfish assemblage since 1991. Special concerns are proposed for the management of these species because they are very slow growing, long-lived, and commercially important.

Marine reserves (harvest refugia) have often been proposed as a valuable management tool for mitigating overfishing and maintaining species and habitat diversity. Their effectiveness in fisheries management, however, is poorly understood and concepts regarding their use are largely untested. Our study investigated the potential role of harvest refugia in the management of these two species by using a Geographic Information System (GIS) application to design harvest refugia networks of varying spatial extent. Twenty-year projections employing a population dynamics model were used to compare ending biomass and fishing mortality under the current management system with biomass and fishing mortality under refuge management systems. The results indicate that harvest refugia can be used to greatly reduce discards and serial overfishing of substocks without reducing current catch levels.

Manuscript accepted 24 July 2000.
Fish. Bull. 99:168–179 (2001).

The potential role of marine reserves in the management of shortraker rockfish (*Sebastes borealis*) and rougheye rockfish (*S. aleutianus*) in the Gulf of Alaska

SungKwon Soh

School of Fisheries, mail stop 357980
University of Washington
Seattle, Washington 98195
Present address: Ministry of Maritime Affairs and Fisheries
139 Chungjong-No 3
Seodaemun-Gu
Seoul, 120-715, Republic of Korea
E-mail address: sksoh@hotmail.com

Donald R. Gunderson

School of Fisheries, mail stop 357980
University of Washington
Seattle, Washington 98195

Daniel H. Ito

Alaska Fisheries Science Center
National Marine Fisheries Service, NOAA
7600 Sand Point Way NE
Seattle, Washington 98115-0070

Over 70 species of rockfish (genus *Sebastes*) inhabit the geographic region between the Gulf of California and the Bering Sea, and many of these species are important components in the groundfish fisheries in this region. Rockfish are viviparous, and several species mature slowly (>5–10 years), have long life spans (50–140 years), and are particularly vulnerable to overfishing. Several species off the Pacific coast currently subsist at dangerously low levels (Murray et al., 1999), and it is anticipated that rebuilding these stocks will require long periods of time (several decades in some cases). Many ecologists and fishery managers see marine reserve (or no-take refuge) networks as an attractive supplement to current management systems in the conservation and management of rockfish stocks (Murray et al., 1999). Our study explores the potential use of harvest refugia in the specific case of shortraker (*S. borealis*) and rougheye (*S. aleutianus*) rockfish in the Gulf of Alaska.

We review the current management system for shortraker and rougheye rockfish in the Gulf of Alaska, describe problems confronted under this system, and suggest refuge management as a supplement to the current management regime. The comparison of future biomass and fishing mortality between the current system and the refuge system will be discussed on the bassis of twenty-year projections from a population dynamics model. The potential impacts of harvest refugia on other Gulf of Alaska fisheries will also be discussed.

Current management system

Groundfish in the Gulf of Alaska are currently managed by the North Pacific Fishery Management Council (NPFMC). Scientists on the Gulf of Alaska groundfish plan team compile a Stock Assessment and Fishery Evaluation report every year. This report includes recommended acceptable biological catch (ABC) levels for each stock and stock complex (including the shortraker-rougheye complex) under the Fishery Management Plan. The NPFMC then

Table 1

Gulf-wide discard rates (%) for the four slope rockfish management subgroups in the commercial fishery during 1991–97. Data are from weekly production and observer reports.

Management subgroup	1991	1992	1993	1994	1995	1996	1997
Pacific ocean perch	15.7	21.5	79.2	60.3	19.8	17.2	14.3
Shortraker and rougheye rockfiish	42.0	10.4	26.8	44.8	30.7	22.2	22.0
Northern rockfish	—	—	26.5	17.7	12.7	16.5	27.8
Other slope rockfish	20.0	29.7	48.9	65.6	72.5	75.6	52.1

considers ABC recommendations, social and economic factors, and determines total allowable catches (TACs). Shortraker and rougheye rockfish are considered as a management unit in the setting of TACs.

In fishery management, fishing seasons are imposed to regulate fishing effort based on three catch levels: total allowable catch (TAC), acceptable biological catch (ABC), and overfishing level (OFL). There is an open, directed fishery (with allowances for bycatch) until the catches reach the TAC level. The TAC level is often lower than the ABC but frequently they have been the same for the shortraker-rougheye rockfish subgroup. Once the ABC is reached, these species are prohibited to be caught and must be returned to the sea. Finally, the fishery is closed when it reaches the overfishing level. A directed fishery for shortraker-rougheye rockfish occurred only in 1991 and 1992; the fishery has since been designated as a bycatch-only fishery.

A constant exploitation-rate strategy has been used for the shortraker and rougheye rockfish subgroup. Fishing mortality for determining ABC was set equal to natural mortality (F=M rule), which, like $F_{0.1}$, was generally considered to be conservative (Deriso, 1987). This has been used to determine ABC since 1991, when these stocks were established as an independent management subgroup of the slope rockfish assemblage. The main reason for using this simple management procedure compared with the more sophisticated one used for Pacific ocean perch and other species is a lack of historical catch data and biological information. In 1997, revised definitions of ABC and OFL replaced the Plan Team's previous procedures (NMFS, 1996): ABC is a preliminary description of the acceptable harvest (or range of harvests) for a given stock or stock complex and overfishing is defined as any amount of fishing in excess of a prescribed maximum allowable rate. For rougheye rockfish, fishing mortality rates for OFL and ABC are determined by

$$F_{OFL} = F_{30\%} \text{ and } F_{ABC} \leq F_{40\%},$$

where "$F_{X\%}$" refers to the fishing mortality rate associated with an equilibrium level of spawning per recruit equal to X% of the equilibrium level of spawning per recruit in the absence of any fishing (Clark, 1991; 1993).

For shortraker rockfish, the equations are $F_{OFL} = M$ and $F_{ABC} \leq 0.75 \times M$ because there is less information for this species.

Fish discards are a serious problem under the current management system because fish are discarded when the catch of a management category attains ABC. Discard rates for the four slope rockfish subgroups in the Gulf of Alaska were estimated as shown in Table 1 (Heifetz et al., 1997). There are two situations which result in discards at sea. One case happens under "bycatch only" status, where theoretically, only a fixed percentage of the haul-by-haul catch can be retained and the rest must be discarded to protect the stocks from a directed fishery. This "retained" catch should be available only when the bycatch status is still open. The other case occurs under prohibited status. If the total harvest exceeds ABC levels, all catch must be discarded.

Shortraker and rougheye rockfish are a slow-growing, long-lived species. Maximum age for rougheye rockfish, for example, is about 140 years (Chilton and Beamish, 1982) and the von Bertalanffy growth parameter, K, for this species is about 0.05. Both shortraker and rougheye rockfish are very large fish; $L_\infty \cong 55$ cm for rougheye rockfish and $L_\infty \cong 72$ cm for shortraker rockfish. McDermott (1994) estimated natural mortality of rougheye and shortraker as 0.030–0.039 and 0.027–0.042, respectively, using the gonadosomatic index method (Gunderson, 1997a). Maturity analysis showed that about 50 percent are mature at 43.87 cm FL (about 20 years) for rougheye rockfish, whereas about 50 percent are mature at 44.90 cm FL for shortraker rockfish (McDermott, 1994).

Rougheye rockfish undertake only limited migrations once they have recruited to the fishing ground (Gunderson, 1997b) and this is generally considered to be true for shortraker rockfish as well. Historical catch locations show specific habitat preferences and a patchy distribution for shortraker and rougheye rockfish in the Gulf of Alaska. Shortraker and rougheye rockfish present in "hot spots" can be readily overexploited by the fishing industry by targeting these spots and harvesting the fish through specialized harvesting skills.

Refuge management

Harvest refugia are areas protected from some or all fishing activities. The general objectives of creating harvest refugia can be discussed with respect to the fish community, fishery practices, and ecological aspects of fish habitat

(Lindeboom, 1995; Bohnsack and Ault, 1996; Allison et al., 1998; Lauck et al., 1998; Yoklavich (ed.), 1998). Conservation of ecological and demographic characteristics, protection of fish habitat, and ensuring recruitment supply under environmental uncertainty and management shortcomings are among the general benefits of harvest refugia. Harvest refugia may also serve as control communities for comparison with nonrefuge areas, allowing us to determine the effects of exploitation on the ecological community and to disentangle the effects of fishing and environmental change.

However, we still lack detailed and scientifically defensible knowledge regarding the effects of harvest refugia. Because of a lack of information on spatial processes for fish populations, there are only a few quantitative assessments of the effects of refugia on current yields and on future abundance of populations (Polacheck, 1990; Roberts and Polunin, 1991; DeMartini, 1993; Holland and Brazee, 1996). The primary information needed for effective design of harvest refugia includes spatial structure of the population, population dynamics, larval drift trajectories, movements of benthic life stages, descriptions of fish habitats, and a distribution of fishing effort. Limited amounts of such information are available for shortraker and rougheye rockfish. Therefore, the establishment of harvest refugia in our study aims to improve the efficacy of the current harvest-rate strategy by providing a safer management scheme by which to conserve shortraker and rougheye spawning populations from possible depletion. This scheme can be used in combination with the current management strategy as an additional control on harvesting and as an attempt to solve problems that characterize the current management policy.

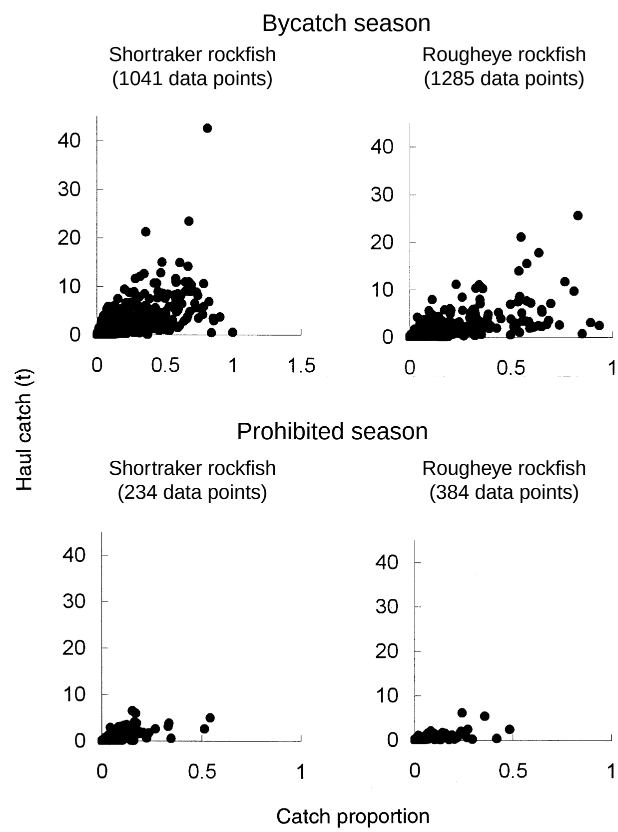

Figure 1

Haul catch of shortraker and rougheye rockfish and the proportion of the total catch made up by these species during the bycatch and prohibited season during 1991–96.

Methods

Documentation of fishery targeting practices

Current management allows vessels to "top-off" their catch during the bycatch season. The purpose of the "bycatch season" is to protect the population from a directed fishery and to allow for "natural" bycatch in other directed fisheries. In theory, targeting of a species can be avoided by allowing retention of only a certain fraction of that species, haul by haul. Such bycatch management measures have failed in instances where fishing deliberately targets bycatch species when their natural bycatch levels are lower than the specified limit. For example, if Pacific ocean perch (POP) is the target species, then vessels can retain bycatch species such as shortraker and rougheye rockfish up to a certain percentage of the total POP catch during the vessel trip. If they prefer, however, they could first fill their bins with POP and then target shortraker and rougheye rockfish. Through "topping-off," the fishery, in essence, becomes a directed fishery for the bycatch species.

To examine the targeting practice for these bycatch species, historical fishing seasons were divided into an allowable bycatch season and a prohibited season, and catch information for each fishing season was compared. During the prohibited season, neither high catches nor high proportions of shortraker and rougheye rockfish occurred (Fig. 1). During the bycatch season, however, both high catches and high proportions were observed. This comparison supports the hypothesis that vessels do target high-value species and that their fishing practices are focused on specific "hot spot" areas. Higher catch-per-unit-of-effort (CPUE) points in regions of short-tow duration (Fig. 2) provide further evidence of the practice of targeting these species. As a result, serial targeting in productive areas would induce early attainment of the ABC and result in discarding afterwards.

Design of harvest refugia

Basic design components of marine refugia are location, size, shape, and number. These components depend on the purpose of the harvest refugia.

In our application, the main goal of establishing harvest refugia for shortraker and rougheye rockfish is to protect adult fish from serial overfishing in areas of high short-

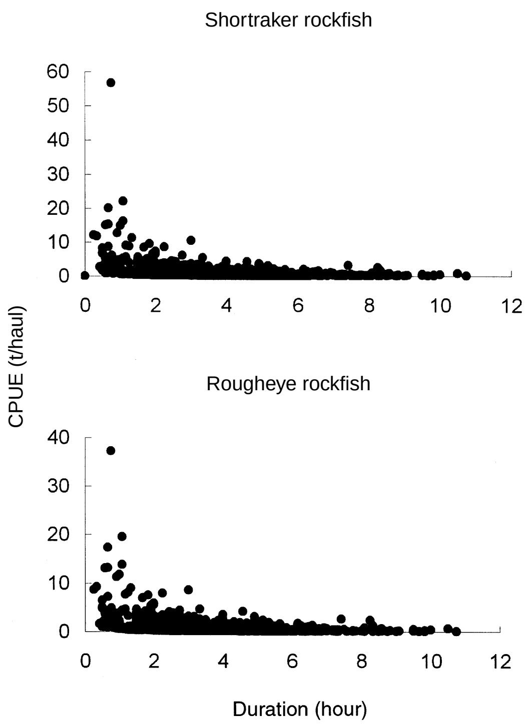

Figure 2

Distribution of haul CPUE (t/haul) versus tow duration for shortraker and rougheye rockfish in the Gulf of Alaska (domestic observer data for trawlers during 1987–96).

raker and rougheye production. Precautions are needed because these stocks are very slow growing, long-lived, and patchy in their distribution. Once "hot spot" stocks are depleted, several decades may be required for them to recover (Francis, 1986). Because this study aimed to develop a method for an objective design of refuge networks and to evaluate the feasibility of alternative management scenarios, no specific area was suggested for practical usage.

Size of refugia was determined by using quantiles from cumulated catch data. The selection of the size for harvest refugia depends on the goals of refuge management in general. Here, three sizes were arbitrarily selected and the effects of refuge size on the fish community and fishery practices were then evaluated. These refuge sizes are referred to as SSR (small-size refugia) MSR (middle-size refugia), and LSR (large-size refugia) and include all 1987–96 catches that exceeded the cutoff points for the 99.8%, 99.5%, and 99.0% quantiles, respectively (Fig. 3). The SSR, MSR, and LSR refugia defined in this manner represented 2.4, 5.4, and 9.5% of the total habitat occupied by shortraker or rougheye rockfish, or by both species.

Because the fishery data only provided net retrieval locations, the exact catch locations of each tow were unknown. This lack of starting-tow locations led us to postulate a circular area around the retrieval point to represent the occurrence of the catch. Although the average tow distance was about 18 km, the width of the continental slope region containing high catches for both species was usually less than 15 km, and trawling was generally conducted along depth contours. Therefore, the basic cell of the harvest refugium was arbitrarily chosen as a 20-km diameter circle, a group of which comprised the refugia for each species. Two species-specific harvest refugia were constructed by using GIS. Because shortraker and rougheye rockfish are currently managed together, the two independent reserves were united in the final design of the harvest refugia. Once a GIS database was established, it became possible to visualize the impact of different design criteria on the spatial distribution of the refuge network almost instantaneously.

Modeling population behavior under refuge management

There were two main goals for the assessment and projection of shortraker and rougheye rockfish stock conditions. The first was to examine the current stock status, to project future biomass, and to evaluate uncertainties in the key parameters under the current management system. The other was to examine the effectiveness of harvest refugia in the management of these species and compare it with the current management system. We employed a population dynamics model to address these goals (Soh, 1998). The model was coded by using AD Model Builder (Fournier, 1994). Determination of parameter uncertainties was based on the Markov Chain Monte Carlo method implemented as part of the AD Model Builder software libraries. Two separate time schedules were used in the modeling process: an assessment section (1961–1996) and a projection section (1997–2016). Inputs to the model included reconstructed catch histories (1961–1996), priors of the parameters, survey biomass estimates, and fixed fishing mortality rates.

Two conditions of fishing mortality were selected for future projection because fishing mortalities in establishing ABC and actual fishing mortalities at sea were not equal. Fishing mortalities used to calculate recommended ABC level were F=0.023 for shortraker and F=0.025 for rougheye rockfish (which were natural mortalities determined by NMFS and referred to as "F for ABC") during 1991–96. These ABC levels were not attained, however, and actual average fishing mortalities estimated by the model were F=0.063 for shortraker and F=0.015 for rougheye rockfish (referred to as "actual F") during 1991–96. If no alternative actions were applied to the current management policy, then projection results under the "actual F" scenario would be more realistic than those under "F for ABC".

In a refuge management system, no fishing was allowed in the refuge areas, and a fixed exploitation rate was applied to the harvestable areas. A major difference between projections of the current management and those of refuge management systems is that refuge management incorporates an adjustment for a discard rate of 29.5% (Table 1) into the system on the assumption that no discards will be necessary under refuge management. As a result,

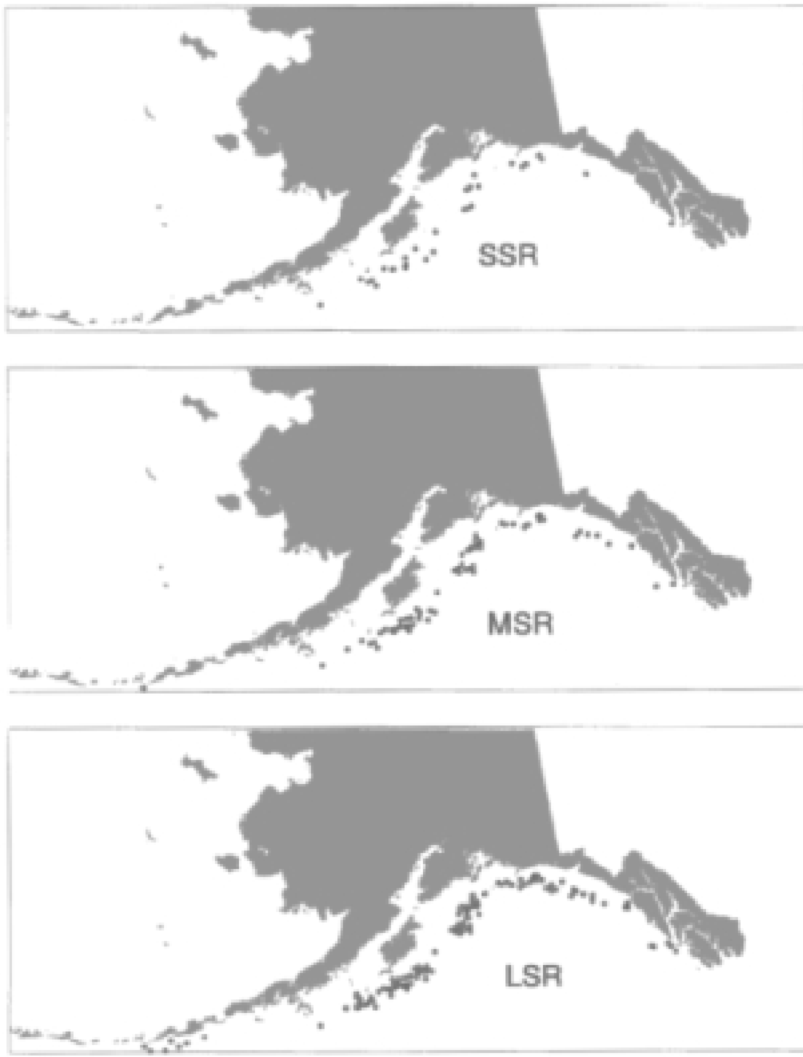

Figure 3

Three sizes of marine refugia are designed and the radius of the basic circle is 10 km. SSR = small-size refugia; MSR = middle-size refugia, and LSR = large-size refugia.

the current actual level of ABC (which includes discards), reduced by average discards, will be applied to future recommended ABC under refuge management. That is, recommended ABC in the harvestable areas will be the recommended ABC under current management multiplied by (1.0 – discard rate), assuming that this average discard rate is constant throughout the future projection years. This reduced ABC does not affect the fishing industry's actual harvest level if they can keep all the catch until ABC is attained.

Considering that they are a very large and valuable species, discards of shortraker and rougheye rockfish are assumed to result primarily from season limits, rather than size limits. Skippers consistently develop their area-specific skills to maximize total income, and high catch rates can result in a short fishing season (Hilborn, 1985). Because harvest refugia in our study were established in high catch-rate zones, or preference zones for shortraker and rougheye rockfish, the harvesting period was assumed to be sufficiently prolonged where shortraker and rougheye rockfish were less dense and regulatory-induced discards would be virtually eliminated as a result.

Model description

A stock reduction analysis model (Kimura et al., 1984) with one-parameter–based Beverton and Holt stock-recruitment relationship (Kimura, 1988) was applied for the stock assessment and future projections. Both analyses were combined to estimate the following relevant parameters:

i = years for the assessment period from 1961 to 1996;
j = years for the future projection period from 1997 to 2016;
λ = weighting factor between survey and fishery information for the combined catch history (= 1.0 when using survey data alone, 0.0 when using fishery data alone);
Q = survey gear efficiency;
d = average annual discard rate;
α = proportion of total biomass in refugia, estimated by cumulated catch data;
M = natural mortality rate;
A = recruitment strength in the Beverton and Holt model;
F_{ABC} = fixed exploitation rate for determining ABC;
ρ = Brody coefficient;
ω = annual growth rate of a fish in weight, $\left(=\frac{W_{k-1}}{W_k}\right)$;
k = age at recruitment;
s = survival rate ($s_i = e^{-(Fi+M)}$);
C^{obs} = observed catches for i and predetermined predicted catches for j;
C^{pred} = predicted catches based on catch equation;
${}^SC$ or ${}^FC$ = reconstructed catches based on survey (S) or fishery (F) information;
B^{obs} = biomass index from surveys;
B = Gulf-wide total predicted biomass;
B^{ref} = predicted biomass in refugia;
B^{nonref} = predicted biomass in nonrefugia;
R = Gulf-wide total recruits;
R^{ref} = predicted recruits in refugia;
R^{nonref} = predicted recruits in nonrefugia.

Stock assessment

Catch histories, based on survey and fishery information, were reconstructed for both shortraker and rougheye rockfish (Soh, 1998). Because survey data were available from 1961 and fishery data from 1977, survey information was used in the construction of catch history for the years 1961–76, whereas an information weighting factor (λ) was applied to combine the two catch histories for the years of 1977–90. Since 1991, independent catch data for the shortraker-rougheye rockfish subgroup have been available. As a result, the combined catch history, which was used as observed catches ($\mathbf{C}^{obs}$) in the model, can be described as follows:

$$\mathbf{C}^{obs} = \begin{bmatrix} C^{obs}_{1961} \\ \cdot \\ C^{obs}_{1976} \\ C^{obs}_{1977} \\ \cdot \\ C^{obs}_{1990} \\ C^{obs}_{1991} \\ \cdot \\ C^{obs}_{1996} \end{bmatrix} = \begin{bmatrix} {}^SC_{1991} \\ \cdot \\ {}^SC_{1976} \\ \lambda^S C_{1977} + (1-\lambda)^F C_{1977} \\ \cdot \\ \lambda^S C_{1990} + (1-\lambda)^F C_{1990} \\ {}^F C_{1991} \\ \cdot \\ {}^F C_{1996} \end{bmatrix}.$$

B^1 is defined as an initial biomass at the beginning of 1961 and R_1 is the recruitment in 1961. The pristine biomass level was assumed to be in an equilibrium state. As a result, initial biomass and the annual recruitment biomass to the unexploited stock can be shown as follows:

$$B_1 = B_0 = B_{1961}$$

$$R_1 = R_{1961} = B_0 \frac{1 - s_0 + \rho(s_0^2 - s_0)}{1 - \rho\omega s_0},$$

where survival rate $s_0 = e^{-M}$.

However, biomass in the second year, B_2, can be defined from the SRA model as

$$B_2 = B_{1962} = (1+\rho)s_1B_1 - \rho s_1 s_0 B_0 + R_2 - \rho\omega s_1 R_1,$$

where $B_1 = B_0$ and survival rate $s_i = e^{-(Fi+M)}$.

R_i is the recruitment biomass at the stock size B_i and is modeled by using a stochastic Beverton and Holt stock-recruitment relationship:

$$R_i = R_1 e^{\varepsilon_i}, \varepsilon_i \sim N(0, \sigma_\varepsilon^2) \text{ for } 2 \le i \le k, \text{ and}$$

$$R_i = R_1 \frac{\frac{B_{i-k}}{B_0}}{1 - A\left(1 - \frac{B_{i-k}}{B_0}\right)} e^{\varepsilon_i}, \varepsilon_i \sim N(0, \sigma_\varepsilon^2) \text{ for } i > k,$$

where k = the recruitment age (assumed k=30).

Since 1963, biomass has been able to be estimated by using the SRA model based on the Deriso's delay-difference equation (1980):

$$B_i = (1+\rho)s_{i-1}B_{i-1} - \rho s_{i-1}s_{i-2}B_{i-2} + R_i - \rho w s_{i-1}R_{i-1} \text{ for } i \ge 3.$$

Future projection of biomass and recruitment

The following biomass and recruitment models were applied throughout the projection period under the current management system:

$$B_j = (1+\rho)s_{j-1}B_{j-1} - \rho s_{j-1}s_{j-2}B_{j-2} + R_j - \rho\omega s_{j-1}R_{j-1}$$

$$R_j = R_1 \frac{\frac{B_{j-k}}{B_0}}{1 - A\left(1 - \frac{B_{j-k}}{B_0}\right)} e^{\varepsilon_j}, \varepsilon_j \sim N(0, \sigma_\varepsilon^2).$$

Under the current management system, F_{ABC} was fixed during the projection period. Predetermined predicted catches ("target catches" or "observed catches") could then be calculated from

$$C_j^{obs} = F_{ABC} B_j.$$

The model stock was divided into two subcomponents under the refuge management system: one for refugia and the other for harvestable areas. Stock within refugia was based on the proportion of Gulf-wide biomass in refugia, α, using the spatial distribution of the historical catches to represent the spatial distribution of the actual exploitable biomass.

Under the refuge management system, target or observed catches were fixed to the level of ABC under the current management system minus the average annual discards:

$$C_j^{obs} = (1-d) F_{ABC} B_j,$$

where d = the average annual discard rate for shortraker and rougheye rockfish.

Gulf-wide recruitment was allocated into refugia and non-refugia areas by using

$$R_j^{ref} = \alpha R_j \text{ and } R_j^{nonref} = (1-\alpha) R_j.$$

Initial biomass for the projection years in refugia and non-refugia, where j = 1, can also be separated at the beginning of 1997 as

$$B_{j=1}^{ref} = \alpha B_{j=1}$$
$$B_{j=1}^{nonref} = (1-\alpha) B_{j=1}.$$

For, j = 2,

$$B_j^{ref} = (1+\rho) s_0 B_{j-1}^{ref} - \rho s_0 s_{j-2} \alpha B_{j-2} + R_j^{ref} - \rho \omega s_0 R_{j-1}^{ref}$$
$$B_j^{nonref} = (1+\rho) s_{j-1} B_{j-1}^{nonref} - \rho s_{j-1} s_{j-2} (1-\alpha) B_{j-2} + R_j^{nonref} - \rho \omega s_{j-1} R_{j-1}^{nonref},$$

where F_i = 0 in refuge.

And for $j \geq 3$,

$$B_j^{ref} = (1+\rho) s_0 B_{j-1}^{ref} - \rho s_0^2 B_{j-2}^{ref} + R_j^{ref} - \rho \omega s_0 R_{j-1}^{ref}$$
$$B_j^{nonref} = (1+\rho) s_{j-1} B_{j-1}^{nonref} - \rho s_{j-1} s_{j-2} B_{j-2}^{nonref} + R_j^{nonref} - \rho \omega s_{j-1} R_{j-1}^{nonref}.$$

All fishing mortalities were estimated by using the Newton-Raphson method (Taylor and Mann, 1983).

According to Bayes theorem, posterior log-likelihood is the sum of prior and experimental log-likelihood, $\log L(\theta \mid X) = \log L(\theta) + \log L(X \mid \theta)$. Therefore, posterior values of the other parameters were evaluated by minimizing the total negative log-likelihood:

$$Total(-\log L) = \frac{1}{2\sigma^2} \sum_i \left\{ \log\left(\frac{QB_i}{B_i^{obs}} \right) \right\}^2 + \frac{1}{2\sigma_\varepsilon^2} \left\{ \sum_i \varepsilon_i^2 + \sum_j \varepsilon_j^2 \right\} +$$

$$\frac{1}{2\sigma_{Q_{prior}}^2} \left\{ \log\left(\frac{Q}{Q_{prior}} \right) \right\}^2 + \frac{1}{2\sigma_{M_{prior}}^2} \left\{ \log\left(\frac{M}{M_{prior}} \right) \right\}^2 +$$

$$\frac{1}{2\sigma_{A_{prior}}^2} \left\{ \log\left(\frac{A}{A_{prior}} \right) \right\}^2 + (\lambda - \lambda_{prior})^2.$$

Priors are listed as follows:

Survey catchability coefficient, Q	$Q \sim N(1, 0.6^2)$
Natural mortality, M	$M \sim N(0.03, 0.2^2)$ for shortraker rockfish
	$M \sim N(0.025, 0.2^2)$ for rougheye rockfish
S-R shape parameter, A	$A \sim N(0.889, 0.2^2)$
Catch information weighting factor, λ	$\lambda \sim Uni(0.001, 0.999)$

Impacts of harvest refugia on other fisheries

Establishing no-take zones obviously affects other fisheries in the zones. Main species in the harvest refugia include Pacific ocean perch (*Sebastes alutus*), shortspine thornyhead (*Sebastolobus alascanus*), northern rockfish (*Sebastes polyspinis*), dusky rockfish (*Sebastes ciliatus*), sablefish (*Anoplopoma fimbria*), and rex sole (*Glyptocephalus zachirus*), as well as shortraker and rougheye rockfish. To examine the impacts of harvest refugia on other fisheries, the effects of depth constraints on refuge areas were considered. The reduction rates of "hot spot" catches by using different depth constraints were compared for each species.

Results

Fixed exploitation-rate strategy

Under an "F for ABC" fishing mortality (F=0.023), the ending biomass of shortraker rockfish would increase by about 800 metric tons (t) in twenty years, but the stock would decrease by over 7000 t if current fishing intensity (actual F=0.063) were continued (Table 2). Rougheye rockfish declined under both "F for ABC" and "actual F" fishing scenarios (either F=0.025 or F=0.015) by about 5000–12,000 t. Although the actual fishing mortality was much lower than the fishing intensity for the recommended ABC, rougheye stocks still declined.

Annual recruits of shortraker and rougheye rockfish ranged from about 1% to 3% of annual biomass based on the recruitment scenario, with a Beverton and Holt shape parameter A=0.889. For both scenarios of "F for ABC" and "actual F" fishing conditions, similar recruitment trends occurred in both species. Because the age at recruitment was assumed to be 30 (Nelson, 1986), future recruitment was not affected by the future fishing mortality schedule during the projection years. Recruitment strength varied relatively little (Fig. 4) and was greatest during the early 1990s.

The estimates of posterior parameter values are shown in Table 3. The mean value of the posterior Q at maximum likelihood was about 0.78 for both species. This value of Q implies underestimation of the actual biomass by the surveys and is consistent with submersible observations by Krieger and Ito (1999), who concluded that the above-bottom distribution of shortraker and rougheye rockfish, together with their preference for steep-slope boulder habitats, would result in a value of Q that was less than 1.0. Natural mortality was estimated to be closer to prior expectations as was the shape parameter (A) in the Beverton and Holt recruitment curve (Beverton and Holt, 1957). Presumably the closeness of prior values and posterior estimates reflects the lack of information about the mortality and stock-recruitment relationship.

The lower posterior value of λ for shortraker rockfish represents more emphasis on fishery information and the increased value of λ for rougheye rockfish represents more emphasis on survey information in the combination of the two catch histories during 1977–90. Survey catch data show that shortraker rockfish are found primarily along the continental slope, whereas rougheye rockfish are distributed more broadly on the continental shelf. Generally, survey coverage in the slope region is relatively sparse, and data are consequently acknowledged to be insufficient. In this regard, more emphasis on fishery information for shortraker rockfish is desirable. The 1996 biomass represented decreases to about 46% and 69% of pristine level (B_{1961}) for shortraker and rougheye rockfish, respectively.

Refugia management strategy

The effects of refuge size on ending biomass, and differences in fishing intensity between current management and refuge management were considered in the projection model of refuge management. Ending biomass in twenty-year future projections and average twenty-year fishing mortality rates were compared for two levels of F ("F for ABC" and "actual F") and three refuge sizes.

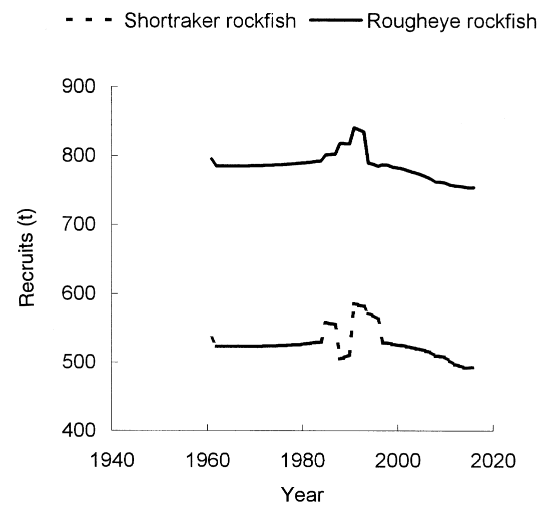

Figure 4

Predicted recruitment trajectories for shortraker and rougheye rockfish using the Beverton and Holt model with shape parameter A = 0.889.

Table 2

Starting and ending biomasses (t) of shortraker and rougheye rockfish under the current management regime, based on a 20-year future simulation (1997–2016). "F for ABC" is the fishing mortality currently used to calculate recommended ABC, and actual average fishing mortality during 1991–96, estimated by stock reduction analysis, is denoted as "actual F".

	Shortraker rockfish		Rougheye rockfish	
Year	F for ABC (F=0.023)	Actual F (F=0.063)	F for ABC (F=0.025)	Actual F (F=0.015)
1997	20,061	20,061	55,896	55,896
2016	20,847	12,623	43,351	50,443

Table 3

Estimates of posterior parameter values and their standard errors. Values in parentheses are standard errors. (B_{1996}=biomass in 1996, M=natural mortality, Q=survey catchability coefficient, A=shape parameter of Beverton and Holt recruitment curve, λ=weighting parameter for survey information in the reconstruction of catch history, and depletion level (B_{1996}/B_{1961})).

	Shortraker rockfish		Rougheye rockfish	
Parameter	Prior	Posterior	Prior	Posterior
B_{1996} (t)	—	20,667 (10,260)	—	56,040 (30,982)
M	0.030 (0.2)	0.031 (0.006)	0.025 (0.2)	0.025 (0.005)
Q	1 (0.6)	0.776 (0.325)	1 (0.6)	0.785 (0.407)
A	0.889 (0.2)	0.889 (0.178)	0.889 (0.2)	0.889 (0.178)
λ	0.5	0.266 (0.565)	0.5	0.554 (0.707)
B_{1996}/B_{1961}	—	0.464 (0.123)	—	0.685 (0.120)

Table 4

Summary of simulations showing ending biomasses (t) and average fishing mortalities from 20-year future projections. Three refuge sizes and two fishing intensity schedules are compared under current and refuge management systems. *F* values under refuge management pertain only to areas outside of refugia. (SSR=small-size refugia; MSR=middle-size refugia; LSR=large-size refugia)

	Ending biomass (year=2016)				Average *F* (during 1997–2016)			
	F for ABC (*F*=0.023)		Actual *F* (*F*=0.063)		*F* for ABC (*F*=0.023)		Actual *F* (*F*=0.063)	
Species	Current	Refuge	Current	Refuge	Current	Refuge	Current	Refuge
Shortraker rockfish								
SSR		23,442		18,270		0.018		0.043
MSR	20,847	23,437	12,623	18,236	0.023	0.022	0.063	0.055
LSR		23,425		18,153		0.030		0.090
Rougheye rockfish								
SSR		50,187		54,764		0.019		0.012
MSR	43,351	50,176	50,444	54,760	0.025	0.023	0.015	0.014
LSR		50,160		54,753		0.030		0.018

Table 5

Percentage of Gulf-wide catches in middle-size refugia (MSR), by species and depth, from domestic observer data (1987–1996). POP = Pacific Ocean perch.

Depth (m)	Shortraker rockfish	Rougheye rockfish	POP	Thornyhead	Northern rockfish	Dusky rockfish	Sablefish	Rex sole
100–713	28	29	15	12	12	17	6	12
200–713	27	28	12	12	1	1	5	6
300–713	23	25	2	9	0	0	3	1

Incorporation of harvest refugia into current management for shortraker and rougheye rockfish resulted in increased ending biomass for both levels of *F* (Table 4). Under the "*F* for ABC" scenario, ending biomass increased about 12% for shortraker rockfish and about 16% for rougheye rockfish with refuge management. Under the "actual *F*" scenario, ending biomass increased about 44% for shortraker and about 8% for rougheye rockfish when refugia were employed. Figure 5 shows the future biomass trajectories for the two management systems. For both fishing intensities, higher Gulf-wide biomass levels were projected in refuge management for both species.

Size differences for harvest refugia had relatively little impact on the ending biomass estimates. Table 4 shows similar ending biomass in refuge management irrespective of refuge sizes for both "*F* for ABC" and "actual *F*" scenarios. This is because the same catch removal was applied, irrespective of refuge size.

Impacts of harvest refugia on other target fisheries

Table 5 summarizes the proportion of catches within refugia compared with those from the whole Gulf for major species in the slope region. About 30% of the Gulf-wide catches of shortraker and rougheye rockfish occurred at depths greater than 100 m in MSR. Out of this, over 80% still remained in MSR in depths greater than 300 m. Dusky rockfish had the next highest proportion in MSR but their distribution was primarily confined to the 100–200 m depth interval. Shortspine thornyhead remained at 9% of the Gulf-wide catch in refugia deeper than 300 m. The catch proportions of other major fishes in refugia deeper than 300 m declined to 3% or less. Clearly, if harvest refugia can be established with depth limits greater than 300 m, then the impacts of no-take zones for shortraker and rougheye rockfish on other fisheries seem minor.

Discussion

Understanding the changes in fishing effort under refuge management is important for its practical application. In refuge management, fishing is allowed only in harvestable areas where fish density is assumed to be less than in refuge areas. However, high levels of fishing intensity outside of refugia are to be avoided because high fishing effort could deplete stocks in nonrefuge areas if adults are sedentary.

The three sizes of refugia resulted in different levels of fishing mortality outside of refugia (Table 4). In the case of middle-size refugia (MSR), fishing mortalities outside of refugia differed little from current Gulf-wide levels. No increased fishing intensity outside of refugia is required under the MSR-based refuge management system, even though harvestable areas are reduced and density is lowered in these areas. It should be remembered, however, that in the projection of refuge management, annual quotas were set to the current annual quotas for shortraker and rougheye rockfish minus discards, and fishermen were assumed to keep all bycatch until quotas were attained. In larger-size refugia (LSR), increased fishing mortality was required in harvestable areas to attain the same amount of quota. Theoretically, this may be acceptable because harvestable areas were reduced and fish density in these areas was less than that outside MSR. In the case of small-size refugia (SSR), fishing mortalities were reduced compared with those under the current management system. Reduced fishing intensity in harvestable areas seem counter-intuitive compared with fishing efforts under the current management system, but this results from applying a reduced annual quota in the refuge management system. However, reduced annual quotas do not mean reductions in landings for the fishing industry because it will probably be possible to keep all catches rather than discard some of them. In this example, lower fishing effort outside of refugia, attainment of the same level of landings for the industry, reduced discards, and increased ending biomass were achieved in refuge management by establishing medium-size or small-size harvest refugia.

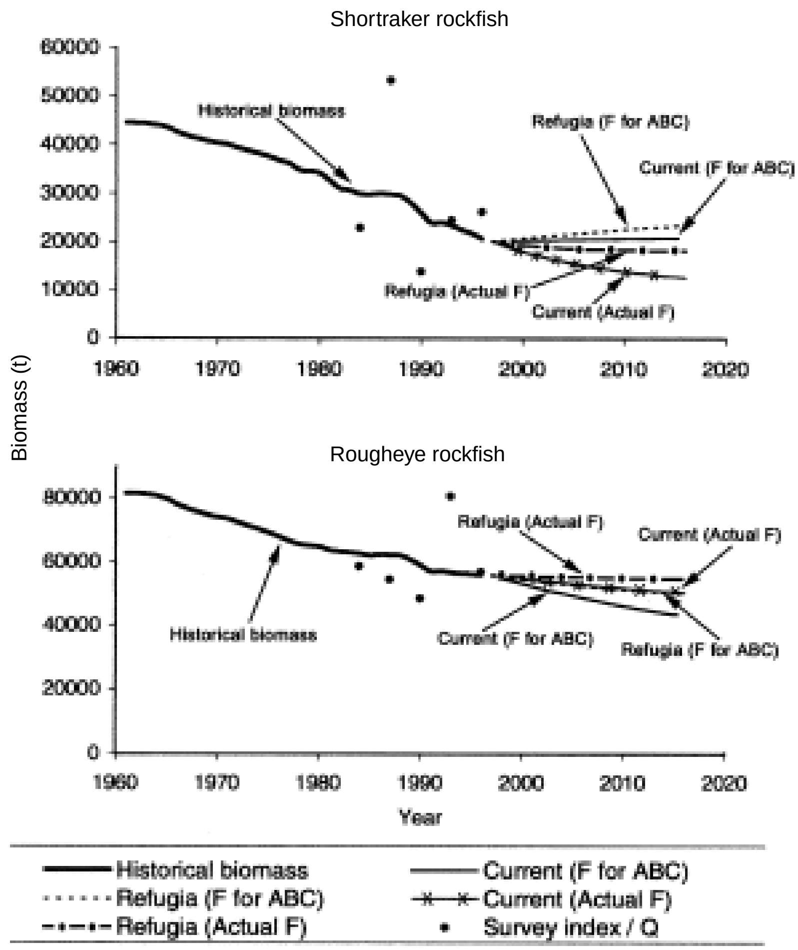

Figure 5

Future Gulf-wide biomass projections for shortraker and roughete rockfish under current management and under refuge management. "F for ABC" is $F = 0.023$ for shortraker and $F = 0.025$ for rougheye rockfish; and "actual F" is $F = 0.063$ for shortraker and rougheye rockfish. Q is a survey catchability coefficient.

Several additional benefits of refuge management for shortraker and rougheye rockfish can be suggested. Harvest refugia can eliminate serial overfishing of the substocks in areas of high densities, i.e. "hot spot" areas. Larger shortraker and rougheye rockfish have been intensively removed during the past two decades. Length-frequency distributions for shortraker and rougheye rockfish show a reduction of larger fish between foreign (1975–1985) and domestic (1987–1996) observer harvesting periods (Soh, 1998). As shown in Figure 5, shortraker rockfish are being overexploited if the goal is to maintain current stock levels. This overexploitation occurs because shortraker and rougheye rockfish are managed together as one subgroup with one combined quota, but shortraker rockfish are generally larger and commercially more valuable than rougheye rockfish.

Discards are an important problem and should be reduced. However, under the current management system, it may be difficult to reduce discards at sea because skippers search for areas with higher catch rates in order to maximize their fishing success. Although the shortraker-rougheye rockfish fishery has been "bycatch only" since 1993, targeting and retaining fish under "topping-off" strategies have continued during the bycatch season (Fig. 1). This type of targeting practice by fisheries allows earlier attainment of ABC and a prolonged discarding period.

Hot spots, or high density zones, for shortraker and rougheye rockfish can be considered as control areas for monitoring and sustaining the surrounding fish stocks. Because we had no information regarding the life stages of these two species prior to recruitment to their fishing grounds, we were at least interested in maintaining adequate spawner biomass in the hot spots. Adult shortraker and rougheye rockfish are reported to live on habitats containing steep slopes (>20°) and numerous boulders (Krieger and Ito, 1999). If these habitats are degraded by fishing activity and if stocks in these areas become reduced, then Gulf-wide stock stability might be at risk. By establishing harvest refugia, essential fish habitat for adult shortraker and rougheye rockfish can be conserved.

Harvest refugia can also be used to ensure an appropriate proportion of shortraker and rougheye rockfish in catches. Because these two species are managed as one subgroup of the slope rockfish assemblage, the fishing season is subject to the attainment of the combined level of two TACs. This management strategy has led to a discrepancy between the intended ABCs and the actual catches of the two species. Trawl survey estimates of exploitable biomass and recommended ABC show species proportions (shortraker to rougheye rockfish) of 3:7 and 4:6, respectively; whereas, commercial catches show a 6:4 ratio. Obviously, this reversed proportion of exploitation between the two species will incur a faster decrease of the shortraker stock than is expected.

Separate management of these two species may be appropriate but because of their overlapping habitat, there could still be excessive waste through discards. Out of all the trawl hauls with either shortraker or rougheye rockfish sampled by domestic observers during 1987–97, about 50% of the total hauls contained both species. By weight, such hauls containing both species accounted for about 72% of the total catch of shortraker and 78% of the total catch of rougheye rockfish. This finding suggests considerable habitat overlap, even though survey data indicate that individual species have somewhat different bathymetric and habitat preferences (Soh, 1998; Ito, 1999). Nevertheless, refuge networks can probably be designed to take advantage of differences in the habitat preference of shortraker and rougheye rockfish to achieve the desired proportions of these species in commercial catches.

In summary, refuge management can potentially be used to solve a number of management problems. By selecting a moderate size, number, and spatial distribution for harvest refugia, the apparent short-term costs or risks can be reduced as much as possible. A solution to the problems of bycatch waste, protection from stock depletion, preservation of essential fish habitat, preservation of the existing spatial distribution of substocks, and prevention of serial depletion of substocks can potentially be achieved through refuge management.

Uncertainties in the results of our study resulted from the fact that populations may behave and adapt differently under different environments with different fishing pressures. Furthermore, there is an uncertainty regarding the sustainability of recruitment owing to a lack of knowledge of larval and juvenile stages and the impact of annual or interdecadal variability in oceanic conditions.

For practical application of a refuge system, additional research is still needed. Optimum shape, location, and size of refugia can best be achieved through adaptive management, by using monitoring and observations from existing refugia to redesign the network. Potential costs or risks, or both, are also expected. The fishing industry needs to be involved in gaining a full understanding of any loss incurred by the displacement of fishing effort from specified areas. Harvest refugia may prove to be unsuccessful if illegal fishing cannot be controlled. Investigation as to how to prevent such illegal behavior and to promote a practical and effective monitoring system still needs to be undertaken.

Acknowledgments

This paper is based on a dissertation by S. K. Soh, in partial fulfillment of the requirements of a Ph.D. at the University of Washington. The research was supported by grants from Washington Sea Grant and the Joint Institute for the Study of the Atmosphere and Ocean (JISAO) under NOAA cooperative agreement no. NA67RJ0155, contribution no. 668.

Literature cited

Allison, G. W., J. Lubchenco, and M. H. Carr.
1998. Marine reserves are necessary but not sufficient for marine conservation. Ecol. Appl. 8 (suppl. 1):S79–S92.

Beverton, R. J. H., and S. J. Holt.
1957. On the dynamics of exploited fish populations. Fisheries Investment Series 2, vol. 19. U.K. Ministry of Agriculture and Fisheries, London.

Bohnsack, J. A. and J. S. Ault.
1996. Management strategies to conserve marine biodiversity. Oceanography 9:73–82.

Chilton, D. E. and R. J. Beamish.
1982. Age determination methods for fishes studied by the groundfish program at the Pacific Biological Station. Can. Spec. Pub. Fish. Aquat. Sci. 60, 102 p.

Clark, W. G.
1991. Groundfish exploitation rates based on life history parameters. Can. J. Fish. Aquat. Sci. 48:734–750.
1993. The effects of recruitment variability on the choice of a target level of spawning biomass per recruit. *In* Proceedings of the international symposium on management strategies for exploited populations (G. Kruse, D. M. Eggers, R. J. Marasco, C. Pautzke, and T. J. Quinn II, eds.), p. 233–246. Alaska Sea Grant College Program Report 93-02.

DeMartini, E. E.
1993. Modeling the potential of fishery reserves for managing coral reef fishes. Fish. Bull. 91:414–427.

Deriso, R. B.
1980. Harvesting strategies and parameter estimation for an age-structured model. Can. J. Fish. Aquat. Sci. 37:268–282.
1987. Optimal $F_{0.1}$ criteria and their relationship to maximum sustainable yield. Can J. Fish. Aquat. Sci. 44(suppl. 2):339–348.

Fournier, D. A.
1994. AUTODIF, A C^{++} array language extension with automatic differentiation for use in nonlinear modeling and statistics. Otter Research Ltd. P.O.BOX 2040, Sidney, British Columbia V8L 3S3, Canada.

Francis, R. C.
1986. Two fisheries biology problems in West Coast groundfish management. N. Am. J. Fish. Manage. 6:453–462.

Gunderson, D. R.
1997a. Trade-off between reproductive effort and adult survival in oviparous and viviparous fishes. Can J. Fish. Aquat. Sci. 54:990–998.
1997b. Spatial patterns in the dynamics of slope rockfish stocks and their implications for management. Fish. Bull. 95:219–230.
Heifetz, J., J. N. Ianelli, and D. M. Clausen.
1997. Slope rockfish. *In* Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska, p. 247–288. [Available from North Pacific Fishery Management Council, 605 W 4th Ave, Suite 306, Anchorage, AK 99501.]
Hilborn, R.
1985. Fleet dynamics and individual variation: why some people catch more fish than others. Can. J. Fish. Aquat. Sci. 42:2–13.
Holland, D. S., and R. J. Brazee.
1996. Marine reserves for fisheries management. Marine Resource Economics. 11:157–171.
Ito, D.
1999. Assessing shortraker and rougheye rockfishes in the Gulf of Alaska: addressing a problem of habitat specificity and sampling capability. Ph.D. diss., Univ. Washington, Seattle, WA, 205 p.
Kimura, D. K.
1988. Stock-recruitment curves as used in the stock-reduction analysis model. J. Cons. Int. Explor. Mer 44:253–258.
Kimura, D. K., J. W. Balsiger, and D. H. Ito.
1984. Generalized stock reduction analysis. Can. J. Fish. Aquat. Sci. 41:1325–1333.
Krieger, K. and D. Ito
1999. Distribution and abundance of shortraker rockfish, *Sebastes borealis*, and rougheye rockfish, *S. aleutinus*, determined from a manned submersible. Fish. Bull. 97:264–272.
Lauck, T., C. W. Clark, M. Mangel, and G. R. Munro.
1998. Implementing the precautionary principle in fisheries management through marine reserves. Ecological Applications 8(1):S72–S78.
Lindeboom, H. J.
1995. Protected areas in the North Sea: an absolute need for future marine research. Helgolander Meeresunters 49:591–602.
McDermott, S. F.
1994. Reproductive biology of rougheye and shortraker rockfish, *Sebastes aleutianus* and *Sebastes borealis*. M.S. thesis, Univ. Washington, Seattle, WA, 76 p.
Murray S. N., R. F. Ambrose, J. A. Bohnsack, L. W. Botsford, M. H. Carr, G. E. Davis, P. K. Dayton, D. Gotshall, D. R. Gunderson, M. A. Hixon, J. Lubchenco, M. Mangel, A. MacCall, D. A. McArdle, J. C. Ogden, J. Roughgardon, R. M. Starr, M. J. Tegner, and M. M. Yoklavich.
1999. No-take reserve networks: sustaining fishery populations and marine ecosystems. Fisheries 24 (11):11–25.
NMFS (National Marine Fisheries Service).
1996. Environmental assessment/regulatory impact review for Amendment 44 to the Fishery Management Plan for the groundfish fishery of the Bering Sea and Aleutian Island area and Amendment 44 to the Fishery Management Plan for the groundfish fishery of the Gulf of Alaska to redefine acceptable biological catch and overfishing, Appendix B. Alaska Fisheries Science Center, NMFS, 7600 Sand Point Way NE., Seattle, WA 98115-0070, 24 p.
Nelson, B. D.
1986. Population parameters of rougheye rockfish (*Sebastes aleutianus*). M.S. thesis, Univ. Alaska, Juneau, AK, 103 p.
Polacheck, T.
1990. Year around closed areas as a management tool. Natural Resource Modeling 4(3):327–354.
Roberts, C. and N. Polunin.
1993. Marine reserves: simple solutions to managing complex fisheries. Ambio 22(6):363–368.
Soh, S. K.
1998. The use of harvest refugia in the management of shortraker and rougheye rockfish (*Sebastes borealis*/*Sebastes aleutianus*) in the Gulf of Alaska. Ph.D. diss., Univ. Washington, Seattle, WA, 194 p.
Taylor, A. E., and W. R. Mann.
1983. Advanced calculus. John Wiley and Sons, New York, NY.
Yoklavich, M., editor.
1998. Marine harvest refugia for west coast rockfish: a workshop. U.S. Dep. Commer, NOAA Tech. Memo. NMFS-SWFSC-255, 159 p.