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Exploitation Rate Reference Points for West Coast Rockfish: Are They Robust and Are There Better Alternatives?

Ray Hilborn [a] , Ana Parma [b] & Mark Maunder [c]

[a] School of Aquatic and Fisheries Sciences , Box 355020, University of Washington, Seattle, Washington, 98195, USA

[b] Centro Nacional Patagonico , 9120 Puerto Madryn, Argentina

[c] Inter-American Tropical Tuna Commission , 8640 La Jolla Shores Drive, La Jolla, California, 92307, USA

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Exploitation Rate Reference Points for West Coast Rockfish: Are They Robust and Are There Better Alternatives?

RAY HILBORN*

School of Aquatic and Fisheries Sciences,
Box 355020, University of Washington,
Seattle, Washington 98195, USA

ANA PARMA

Centro Nacional Patagonico,
9120 Puerto Madryn, Argentina

MARK MAUNDER

Inter-American Tropical Tuna Commission,
8640 La Jolla Shores Drive,
La Jolla, California 92307, USA

Abstract.—We explore several aspects of the robustness of exploitation rate reference points as a management tool. The spawner−recruit curve is an important consideration when developing exploitation rate reference points. The spawner−recruit curves for West Coast rockfish *Sebastes* spp. suggest low productivity compared with other stocks, but our ability to produce reliable estimates of productivity is hindered by the scarcity of reliable, fishery-independent surveys, the short time span of the data, high aging error, and the low exploitation levels. Implementation of reference exploitation rates usually assumes that we can estimate the absolute stock size and the ratio of current to virgin stock size. We show that management by reference exploitation rates is not robust to overestimation of stock size; in such cases, overexploited stocks will continue to be overexploited. We also show that if $F_{55\%}$ exploitation rates (i.e., rates that reduce the spawning potential per recruit to 55% of its value in the unfished state) are used and productivity for an individual stock is comparable to that for other stocks around the world, we would unnecessarily impose catch reductions. We evaluate a management policy that seeks to maintain healthy stocks at or near current levels regardless of the absolute abundance, and we show that such a policy produces desirable results both when the stock size is overestimated and when stock productivity is underestimated. For stocks that are judged to be in need of rebuilding, current management policies seek to reduce catch to very low levels regardless of the reference point.

Fisheries management is the process of establishing institutions and regulations to provide long-term sustainable benefits in the form of food, employment, recreation, and income to society from fish stocks. It is both an art and a science. Successful fisheries management institutions are characterized by the ability to regulate the harvest of the stock and to monitor changes in its abundance. The well-publicized failures in fisheries management can normally be ascribed either to the institutional inability to reduce exploitation when it was recognized that such reductions were needed or to the failure to correctly determine stock abundance.

These two elements are closely related. The ability to regulate harvest depends primarily on the willingness of the harvesters to accept regulation. When the fishing industry does not feel that catch reductions are required, there almost always exist political mechanisms to impede regulations. Fisheries that have a good record of reducing catches in response to scientific advice almost always involve acceptance by the fishing industry of the need for such restrictions. This, in turn, usually means that the industry has confidence in the data that are used to determine the changes in abundance.

The ability to monitor abundance also depends strongly on the industry's acceptance of the management institution. Good abundance estimates normally depend on good catch records, along with good understanding of discarding, fishing patterns, and stock distribution. When the fishing industry has little confidence in the regulatory institutions, it is much more difficult for the institutions to obtain appropriate data.

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* Corresponding author: rayh@u.washington.edu

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The Pacific Fisheries Management Council (PFMC) has adopted a policy of reference points for management (see Dorn 2002, this issue, for a review of the history of reference points within the PFMC). These reference points are rules for determining target exploitation rates. Throughout this paper, all exploitation rates (F) will be assumed to be discrete, that is, equal to the annual catch divided by the population size at the beginning of the year. When evaluating reference points for fisheries management, we must recognize that the reference points are not an end in themselves but rather one part of a regulatory system meant to help achieve management goals. Thus, we need to consider the implications of these reference points within the entire system, always keeping our eye on the ultimate goal: sustainable benefits to society.

The current review of reference points is prompted by the concern raised by MacCall (2002, this issue) that West Coast rockfish (*Sebastes* spp. and some relatives) may be systematically less productive than the fish stocks that are used to guide the formulation of $F_{35\%}$ and $F_{40\%}$ (the fishing rates that result in spawning potential per recruit values equal to 35% and 40% of their unfished values, respectively) policies. If this hypothesis is correct, current exploitation rates are too high and continued use of these rates will result in fishing the stocks down to levels that are lower than desired, ultimately reducing long-term yield. Moving to lower exploitation rates would result in immediate catch reductions for the affected fish stocks, which may be unnecessary if the productivity of these stocks has been underestimated.

Spawner–Recruit Relationships and Reference Points

Myers et al. (1995) have compiled spawner–recruit data from hundreds of fish stocks and estimated spawner–recruit parameters for these stocks (Myers et al. 2002, this issue) . These parameters are estimated on the basis of the assumptions that the spawning stock is measured without error and that the underlying spawner–recruit relationship has not changed over time. Any fitted spawner–recruit curve, combined with age-specific data or assumptions about natural mortality and fecundity, can be used to calculate two useful quantities: the spawning stock size at which the population would come to equilibrium in the absence of harvesting (often called the virgin or unexploited biomass) and the sensitivity of recruitment to reductions in spawning stock (often called steepness).

Steepness is a particularly important quantity because it is a measure of the potential ability of the stock to sustain exploitation. Stocks with high steepness can sustain higher exploitation rates and provide more sustainable yield (relative to the virgin biomass) than those with lower steepness. Myers et al. (2002) reviewed the estimated spawner–recruit curves for many stocks in search of life history parameters that could be correlated with steepness. The best explanatory variable they found was total lifetime reproductive output, which is closely related to the natural mortality rate. Stocks with a high natural mortality rate tend to have low total lifetime reproductive output and, on average, appear to have lower steepness as well.

Dorn (2002) conducted a meta-analysis of the stock productivity for a number of West Coast groundfish stocks and found that several of these stocks appear to have low spawner–recruit steepness, especially Pacific ocean perch *S. alutus* (south of Canada), bocaccio *S. paucispinis*, canary rockfish *S. pinniger*, and widow rockfish *S. entomelas*. On average, the productivity of U.S. West Coast rockfish was estimated to be lower than assumed by Clark (1991, 1993) in the original work used to formulate the reference levels $F_{35\%}$ and $F_{40\%}$. There are at least three possible hypotheses for this:

Hypothesis I.—The estimated steepness is correct, and West Coast rockfish systematically have a lower spawner–recruit steepness than most other stocks.

Hypothesis II.—The apparent spawner–recruit curve reflects environmentally driven poor recruitment in the last two decades that coincides with the unproductive phase (for the U.S. West Coast) of the Pacific Decadal Oscillation (Francis and Hare 1994; Beamish 1995). Under this hypothesis, the high recruitment that characterized that climatic regime prior to 1977 built the stocks up to levels that could not be maintained during the post-1977 period even in the absence of harvesting. The decrease in recruitment coincided with a period of increasing exploitation rates and declining trends in abundance. While one could, in theory, fit a spawner–recruit curve with an environmental effect to evaluate the significance of the 1977 shift in productivity, the power of such an analysis would likely be low because data series for West Coast rockfish are short. Since only one major regime shift has been observed, the environmental effects and steepness estimates are highly confounded.

Hypothesis III.—The estimated spawner−recruit relationships are biased, and actual productivity is higher than is apparent. There are a number of factors that make the ability to estimate spawner−recruit relationships for West Coast rockfish less reliable than is possible with most of the datasets used in the Myers et al. (2002) analysis: (1) the time series tend to be short relative to the longevity of the species involved; (2) the low exploitation rates for rockfish mean that recruitment estimates are not closely tied to observed catches but rather depend upon assumptions regarding natural mortality rates and initial stock sizes; (3) there tend to be few observations at the low stock densities that provide the most useful data for estimating stock productivity; (4) there are few reliable, fishery-independent surveys; and (5) there is often high aging error. As Dorn (2002) noted, all of his analyses assume that the spawner−recruit numbers that emerge from the stock assessments are correct, so that any estimates of uncertainty in his analysis are underestimates.

Because we cannot estimate the spawner−recruit relationships, and thus the underlying productivity, with much reliability, we need to seek harvest policies that are robust to uncertainty about stock productivity.

The Precautionary Approach and Harvest Policies

Fisheries can be managed well if one can (1) measure abundance and (2) regulate harvest. The U.S. West Coast rockfish fishery is plagued by the difficulty in surveying many species and problems in regulating and estimating the harvest through the system of trip limits, which leads to discards and offers fishermen few incentives not to catch heavily exploited species. In contrast, in the Canadian groundfish fishery, fishermen must stop fishing in an area if they no longer hold quotas for all the species they might catch. Thus, there is little overrun of catch and no major discard problems in that fishery. This is accomplished via 100% observer coverage and a program of individual vessel quotas (IVQs). While the Canadians, at present, have even fewer sources of fishery-independent data, their ability to estimate and regulate harvests makes their system intrinsically more precautionary.

As agencies have sought to take a precautionary approach to fisheries management, the predominant strategy has been to adopt more conservative reference points. The United Nations Food and Agriculture Organization (FAO) expert consultation on the precautionary approach to fisheries management (FAO 1996) made strikingly different recommendations. The FAO recommendations are primarily procedural and institutional; they describe a precautionary system as one that avoids overcapacity and irreversible actions, responds to changes in abundance promptly, and has legal and institutional frameworks for the development of fishery management plans.

The FAO (1996) also suggests that ‘‘the standard of proof to be used in decisions regarding authorization of fishing activities should be commensurate with the potential risk to the resource, while also taking into account the expected benefits of the activities.’’ These points deal with setting up appropriate institutional frameworks rather than providing any specifics about how much to reduce exploitation rates. The most nonprecautionary aspects of the West Coast rockfish fishery are the difficulty in monitoring abundance and the complexity of the system for estimating and regulating catch.

In the following section, we show that given the uncertainty in stock productivity and absolute stock size, a management system that is based on reference exploitation rates is not precautionary and poses threats of overexploiting stocks when abundance is low and reducing catches unnecessarily when productivity is high. We propose a simpler management system that provides more protection for depleted stocks and more protection for the fishing industry from catch reductions if they are not needed.

Robustness of Reference Points and Alternatives

We saw earlier in this paper and in other papers (Dorn 2002; MacCall 2002) that there is great difficulty in estimating the underlying spawner−recruit curve for West Coast rockfish, as indeed there is for most fish populations. However, management that is based on reference points for F depends not only on the spawner−recruit curve but also on the current stock size (in fixed-exploitation-rate strategies) and the virgin stock size (in the 40:10 rule adopted by the PFMC), estimation of which is problematic. There are a few fisheries that attempt to estimate F directly and to adjust it by regulation without any direct estimate of catch or stock size, but these are reasonably rare.

In a exploitation rate strategy, the total allowable catch (TAC) is calculated as follows:

$$\mathrm{TAC} = u_{\mathrm{ref}} \cdot \hat{B}, \tag{1}$$

where u_{ref} is the reference exploitation rate and $\hat{B}$ is the estimated stock size.

Our ability to measure the absolute size of a marine fish stock is poor, and while there have been no systematic reviews that we are aware of, numerous case studies indicate that fisheries scientists are frequently off by a factor of two to three in their estimates of abundance. The International Pacific Halibut Commission (IPHC) has an assessment program and a permanent staff that is fully dedicated to a single stock. Although it has an excellent track record with respect to long-term sustainable management, in recent years its estimates of the biomass of Pacific halibut *Hippoglossus stenolepis* were first revised upward more than twofold and then revised downward again, mostly in response to changes in assessment methodology (Sullivan et al. 1999) . Throughout the 1980s, the Canadian Department of Fisheries and Oceans (CDFO) systematically overestimated the size of the stock of northern Atlantic cod *Gadus morhua* in Newfoundland by a factor of two (Harris 1990). It is usually difficult to determine the absolute abundance even in retrospect. The IPHC is still uncertain about the best model structure for the assessments, but their current best models suggest that their old model grossly underestimated recruitment in the 1990s. The CDFO is quite confident that they overestimated the stock abundance simply because they caught all the fish and thus knew how many had been there. Walters and Pearse (1996) have argued that any form of management by setting quotas is highly risky because of our inability to measure stock size reliably, and quotas are almost always set based on stock size.

The PMFC's 40:10 rule for rockfish management can be graphed as shown in Figure 1 and written as follows:

$$\mathrm{TAC} = \begin{cases} u_{\mathrm{ref}} \cdot \hat{B} & \text{if } \hat{B} > 0.4\hat{B}_0 \\ 0 & \text{if } \hat{B} < 0.1\hat{B}_0 \\ 0.4\hat{B}_0 u_{\mathrm{ref}} \left(3.333\dfrac{\hat{B}}{\hat{B}_0} - 0.333 \right) & \\ & \text{if } 0.1\hat{B}_0 < \hat{B} < 0.4\hat{B}_0. \end{cases} \tag{2}$$

The new element in the 40:10 rule is the estimate of virgin biomass, B_0. The TAC is a proportion of the exploitable biomass, and the 40:10 adjustment is based on female spawning biomass. As explained earlier, B_0 is often estimated from the estimated spawner−recruit curve or (perhaps more commonly) by taking the estimated average recruitment over the early years of the available data and calculating the population size that would result from that level of recruitment in the absence of exploitation.

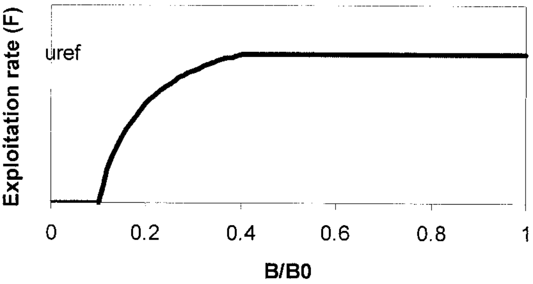

FIGURE 1.—Desired exploitation rate as a function of the ratio of current to virgin biomass (B/B_0) using the Pacific Fisheries Management Council's 40:10 rule. The variable u_{ref} is the target exploitation rate when the stock is greater than 40% of B_0.

Thus, the estimate of B_0 is at least as uncertain as our estimate of current stock size because it is affected by the same scaling factors; if we have underestimated or overestimated the current stock size, then our estimate of recruitment and B_0 will be off by similar factors. This may not be too serious because then the quantity $\hat{B}/\hat{B}_0$ will actually be unbiased. However, numerous other errors also come into estimating B_0. The recruitments over the period of our assessment may not be representative of the long-term average. If the stock has been heavily exploited, then recruitment may be below average and we would underestimate B_0. If there has been any systematic change in environmental conditions (such as a regime shift), then our estimate of B_0 will be biased. If there is density-dependent growth, B_0 will be biased. Indeed, as soon as we consider systematic changes in environmental conditions, it becomes difficult to even define B_0 and other management quantities of interest (Maunder 1998). In some assessments, B_0 may be estimated from cumulative removals, in which case it will be reasonably unaffected by the current stock size but very sensitive to the reliability of the catch data.

In short, any assessment of the performance of the 40:10 rule or other management rules based on reference points should consider the wide uncertainty in estimating not only u_{ref} but also B and B_0. As a simple illustration, consider a stock that is currently estimated to be 100,000 metric tons, with a B_0 of 250,000 metric tons (i.e., the current stock size is 40% of the virgin stock size). While

TABLE 1.—Actual exploitation rates, resulting from different real stock sizes when the estimated current stock size is 100,000 metric tons.

Desired exploitation rate	Real stock size (metric tons)		
	25,000	50,000	100,000
0.06	0.24	0.12	0.06
0.10	0.4	0.2	0.10

we may well be underestimating stock size, management concerns are primarily related to the possibility that we are overestimating the potential productivity of the stock or its abundance. Thus, let us examine the consequence of using reference exploitation rates if we have overestimated the stock size. Assume that $F_{55\%}$ is 0.06 and $F_{40\%}$ is 0.10, which are roughly the estimates for the life history of a rockfish that has a mortality rate (*M*) of about 0.1 and that is 50% mature by age 6 or 7. Also, let us assume that we have correctly estimated the current stock size in relation to B_0. Overestimation of abundance causes the resultant exploitation rates to be higher than the target rates by the same factor that the stock is overestimated (Table 1).

To evaluate the consequences of stock overestimation over a longer term, we have constructed a simulation model (described in Appendix I). While this model is quite flexible, we will present some results based on the following, considerably simplified key assumptions:

(1) The simulation fishes a ‘‘true’’ population by using various rules; none of these rules know the ‘‘true’’ population.

(2) The true population is derived from a standard age-structured model with fishing and natural mortality. Recruitment is generated by means of a Beverton–Holt relationship.

(3) The life history of a moderately long-lived rockfish with a natural mortality rate of 0.08, full maturity and vulnerability at age 13, and half maturity and vulnerability at age 6 is used.

(4) The bias in the estimated stock size will persist over time, that is, if we currently estimate the stock size as twice its real value, we will continue to do so throughout the period of analysis.

(5) The ratio between the stock size and B_0 is estimated without error (this is assumed for the runs below, but the equations in Appendix I are more general).

(6) When using the 40:10 rule, the estimated stock size and B_0 are applied using equation set (2).

(7) As an alternative to the reference exploitation rate policies, we simulated a policy that assumes we have a relative index of abundance (such as a survey or stock assessment) and that tries to regulate the catch to keep the stock at the current index size.

The results of implementing a policy with $F = 0.06$ and the 40:10 rule when the stock is believed to be 100,000 metric tons but is really 25,000 metric tons are shown in Figure 2. (This simulation assumes that the bias in estimating B_0 is the same as that in estimating *B* and that the estimated value of B/B_0 was 0.40 initially.) We can see from Figure 2A that the target exploitation rate begins at 0.06 but that as the stock declines below 40% of B_0 the 40:10 rule is activated and the exploitation rate is decreased. However, since we are systematically overestimating the stock size, $F = 0.06$ is actually a 24% exploitation rate, and the stock declines.

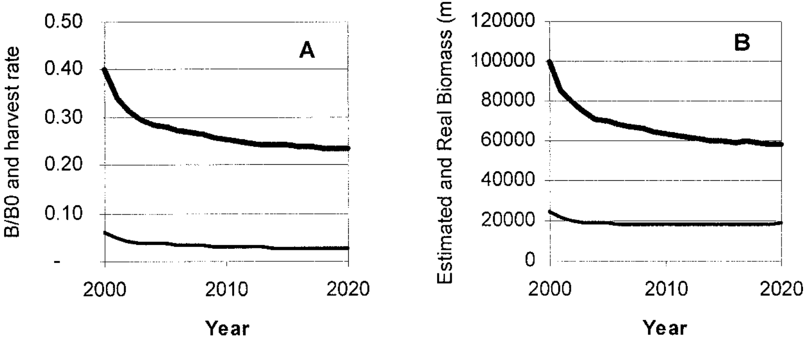

FIGURE 2.—Trends in **(A)** B/B_0 and the target exploitation rate (heavy and light lines, respectively) and **(B)** real and estimated abundance (light and heavy lines, respectively) when a 40:10 rule is applied with a reference exploitation rate of 0.06 and the initial stock size is 25,000 metric tons but is estimated to be 100,000 metric tons.

TABLE 2.—Results of applying different management policies to a population with an estimated abundance of 100,000 metric tons and a known initial stock size (B_0) of 250,000 metric tons. Simulations were done under nine hypotheses representing different combination of steepness and true initial stock size. The final column shows expected values assuming that the probability of each hypothesis is the same. Three policies are considered: the ‘‘hold steady’’ policy, in which average catch is adjusted to keep the relative abundance at the same level, and policies with target exploitation rates (F) of 6% and 10%. The last two policies are adjusted by the Pacific Fisheries Management Council’s 40:10 rule (see text) when the stock is estimated to have dropped below 40% of B_0. The table is grouped into three major sections, showing average catch (metric tons), biomass after 20 years (B[20]) relative to B_0, and biomass after 20 years relative to biomass in the first year.

Variable and policy	Hypothesis									Expected value
	1	2	3	4	5	6	7	8	9	
Steepness	0.4	0.6	0.8	0.4	0.6	0.8	0.4	0.6	0.8	
True initial stock size (metric tons)	25,000	25,000	25,000	50,000	50,000	50,000	100,000	100,000	100,000	
					Average catch					
Hold-steady	2,263	4,959	8,376	3,497	6,708	9,641	4,081	6,582	8,243	6,039
$F = 0.06$	2,345	4,703	7,728	3,856	6,255	7,852	5,091	6,389	6,983	5,689
$F = 0.10$	2,390	4,644	8,128	4,210	6,882	9,567	6,131	8,034	9,371	6,595
					$B(20)/B_0$					
Hold-steady	0.10	0.10	0.10	0.21	0.21	0.22	0.42	0.43	0.43	0.25
$F = 0.06$	0.07	0.11	0.18	0.17	0.24	0.33	0.36	0.44	0.50	0.27
$F = 0.10$	0.06	0.09	0.12	0.14	0.19	0.22	0.29	0.35	0.38	0.20
					$B(20)/B(1)$					
Hold-steady	1.00	1.01	1.01	1.04	1.07	1.10	1.04	1.07	1.09	1.05
$F = 0.06$	0.75	1.15	1.84	0.86	1.21	1.64	0.89	1.10	1.25	1.19
$F = 0.10$	0.59	0.88	1.18	0.68	0.93	1.11	0.73	0.88	0.96	0.88

The trends in the real and estimated stock size are depicted in Figure 2B.

The ‘‘hold-steady’’ policy can be written in terms of the following equations:

$$C_{t+1} = C_t \cdot \mathrm{cLag} + (1 - \mathrm{cLag})D,$$

where

$$D = \begin{cases} 0 & \text{if } I_t < I_{\text{target}} \\ I_t - I_{\text{target}} & \text{if } I_t > I_{\text{target}} \end{cases} \tag{3}$$

and C_l is the value of TAC at time t; cLag is a buffering factor to stabilize the catch from one year to the next (a value of -0.8 is used in the figures below); D is the desired catch based on the index of abundance; I_t is the index of abundance at time t; and I_{target} is the target index of abundance.

Essentially, this rule represents a fixed-escapement policy. When the index of abundance exceeds the target level, desired catch is the difference between the two; when the index of abundance is below the target level, desired catch is zero. Ideally, I will be in the same units as catch and biomass, but this is not required as the desired catch will keep decreasing as long as I is dropping. The values of cLag are chosen to provide different levels of buffering. Also, the actual average index level is not at I_{target} when cLag is greater than zero. In the runs below, cLag = 0.8 and $I_{\text{target}} = 90{,}000$.

A range of simulations over different stock conditions were run (Table 2). As the results are complex, let us begin with the second column of the table, which represents hypothesis 1. The first row shows the true steepness for the population, which in this case is 0.4 (a low value indicative of an unproductive stock that is only capable of relatively low long-term yields). The second row shows the true initial stock size, in this case 25,000 metric tons; as our estimate of the stock size is 100,000 metric tons, in this scenario we are seriously overestimating (by a factor of 4) the true stock size. Following this row are three blocks of results, namely, (1) the average catch over a 20-year period, (2) the ratio of the average population size to B_0, and (3) the ratio of the average population size (after 20 years) to the initial population size. The next eight columns show the results for eight other hypotheses, comprising steepness values of 0.4, 0.6, and 0.8 for real stock sizes of 25,000, 50,000, and 100,000 metric tons.

The last column shows the expected values, assuming that each of the nine hypotheses has an equal probability of being true. Within each block there are three rows representing three manage-

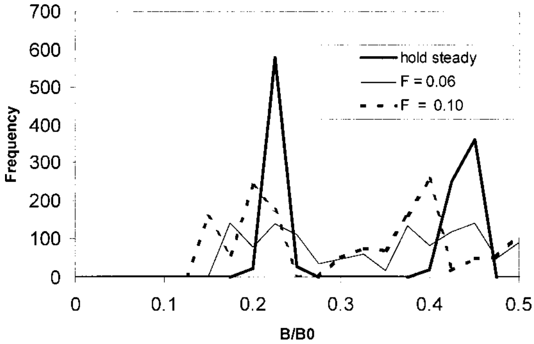

FIGURE 3.—Frequency distribution of stock size expressed as a fraction of unfished biomass (B/B_0) for the three policies considered.

TABLE 3.—Consequences of a 50% unreported catch. The values in the column headed ''No unknown catch'' are from Table 2. All results are computed as expectations across the hypotheses given in Table 2; see that table for additional details.

Policy	No unknown catch	50% extra catch
	Expected catch	
Hold-steady	6,039	4,061
$F = 0.06$	5,689	4,320
$F = 0.10$	6,595	4,637
	$B(20)/B_0$	
Hold-steady	0.25	0.24
$F = 0.06$	0.27	0.21
$F = 0.10$	0.20	0.17
	$B(20)/B(1)$	
Hold-steady	1.05	0.98
$F = 0.06$	1.19	0.92
$F = 0.10$	0.88	0.74

ment policies, namely, (1) the hold-steady policy, which adjusts catches so that the stock index stays close to its level in the first year, (2) the $F = 0.06$ policy, which corresponds to an $F_{55\%}$ policy, and (3) an $F = 0.10$ policy, which corresponds to an $F_{40\%}$ policy. Hypothesis 1 represents the worst possible (true) state of the stock, as it is both much smaller than estimated (25,000 metric tons versus 100,000 metric tons) and unproductive (steepness = 0.4).

We see that the $F = 0.10$ policy has the highest average catch and the lowest average stock size, while the $F = 0.06$ policy has the lowest catch and highest stock size. Note, however, that the exploitation rate policies tend to rebuild the stock when the steepness is high but to deplete it when the steepness is low. It would be better if the opposite were true, namely, that stocks with higher steepness maximized their yield at lower stock sizes while stocks with lower steepness maximized yield at higher stock sizes.

For the most pessimistic hypothesis, the first block shows us that the catches are 2,263 metric tons for the hold-steady policy, 2,345 metric tons for the $F = 0.06$ policy, and 2,390 metric tons for the $F = 0.10$ policy. While these differences are small, there are much bigger ones in the third block, where we see that under the hold-steady policy the stock abundance averages 100% of its initial value, compared with 75% and 59% for the two reference points policies. The second block shows us that while the hold-steady policy keeps the population at 10% of its virgin abundance, the other two policies further deplete this stock, clearly an undesirable outcome.

A major concern of the fishing industry is that for stocks for which the true productivity is high, moving to an $F_{55\%}$ policy would result in unnecessary reductions in catch. A long-term analysis such as Dorn (2002) has conducted tends to hide the immediate reductions in catch. While productive stocks will attain higher levels under a low exploitation rate—so that in the long term there may not be a major loss in average catch—the short-term consequences would be large catch reductions that would be unnecessary if productivity is not low. A hold-steady policy would avoid such reductions for productive stocks.

Another way to view the output of these analyses is to look at the distributions rather than the expected values. The frequency distributions of stock size for the three policies examined are shown in Figure 3. Each of the policies has a bit of a local mode at the three major stock size hypotheses (10, 20, and 40%). The 10% exploitation rate policy tends to deplete the stocks a bit more than the other two policies.

A common problem in fisheries is unreported catch, either discards or unreported landings. Policies that attempt to meet an exploitation rate target through such measures as trip limits and area closures (as is done in the case of West Coast rockfish) will face problems if the estimated catch is inaccurate. The expected results, averaged across all hypotheses, when there is an additional 50% unknown catch are shown in Table 3. The first column reports the expected values from Table 2 with no unknown catch, the second column the consequences with the unknown catch. We see that the hold-steady policy would be much more robust to unknown catch because it simply implements more and more restrictions to try to hold the stock at its current level. In contrast, the policies that are based on reference exploitation rates perform more poorly because as the stock declines owing to excessive removals from the unknown catch, the only form of feedback is the declining target exploitation rate.

In the results shown thus far, we have only examined cases in which the population size was overestimated or correctly estimated. We also ran a simulation in which the true population size was 150,000 metric tons but we estimated it to be 100,000 metric tons. In this case, the hold-steady policy maintains the population in its higher, underexploited state, while the 6% exploitation rate produces a 30% higher yield by fishing the population down a little and the 10% exploitation rate produces a 70% higher yield by reducing the population further. In no case, however, does the population drop below 40% of its unfished state. Thus, the hold-steady policy forgoes some potential yield from fishing the stock down in a sustainable fashion.

Discussion

It may well be that many West Coast groundfish stocks have low productivity and the appropriate long-term exploitation rates are lower than those that result from $F_{35\%}$ or $F_{40\%}$ policies. However, for some rockfish stocks (chilipepper *Sebastes goodei* and Pacific ocean perch in Canada and Alaska), productivity is estimated to be higher (Dorn 2002). The management agency should search for a management policy that is robust to this uncertainty.

In this paper, we have demonstrated that the 40:10 policy is not robust either to large overestimation of the stock size or to underestimation of stock productivity and actual catch. In some of these cases, the 40:10 policy results in undesirable consequences for either the stock or the fishery when combined with $F_{55\%}$ reference rates. The hold-steady policy that we evaluated by simulation is simply one of a range of other policies that may be more robust in some circumstances and provide both protection for fish stocks and stability of the catch for the commercial industry. Such hold-steady policies are not new to fisheries. Magnusson and Stefansson (1989) and Bell and Stefansson (1998) have suggested similar policies, which are quite similar to fixed-escapement policies (Hilborn and Walters 1992). We believe that harvest policies need to be evaluated on a case-by-case basis, where the uncertainty in stock size, the reliability of the abundance index and catch estimation, and the life history parameters of the stock are all evaluated. Hold-steady policies may provide a better alternative for some stocks and should be considered.

Our analysis has been predicated on a stock assessment and management system that attempts to measure catch and estimate abundance through a stock assessment. In fisheries where this is not the case, clearly neither a 40:10 nor a hold-steady policy would be appropriate. The fishery management plan for an individual stock should be robust to the uncertainty in stock size estimation and biological parameters, and it seems unlikely that a one-size-fits-all policy like the 40:10 will be appropriate in all circumstances.

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Appendix: Technical Description of Management Strategy Simulations

TABLE A.1.—Specified parameters.

Parameter	Description
z	Steepness of the stock-recruitment relationship
v_a	Age-specific selectivity
M_a	Age-specific natural mortality
S_{init}	Initial spawning biomass
m_a	Age-specific maturity
f_a	Age-specific fecundity
σ_r	Standard deviation of the recruitment variation
κ_r	Recruitment autocorrelation parameter
ϕ	Intercept of the linear catch equation
λ	Slope of the linear catch equation
bias	Bias in the survey biomass estimate
cLag	Catch autocorrelation parameter
$\hat{B}_1$	Biomass estimate in the first year
σ_B	Standard deviation of the biomass estimate
κ_B	Biomass estimate autocorrelation parameter
$a\text{max}$	Maximum age in the model used to accumulate all older fish

Dynamics

A simple age-structured population dynamics model based on a difference equation is used to project the population into the future. The model's parameters are described in Table A.1, and the state, random, and intermediate variables are described in Table A.2. The fishery occurs at the start of the year before there is natural mortality. Recruitment varies annually with an autocorrelation factor. The oldest age-class includes all older fish.

$$N_{y+1,1} = \frac{S_y}{\alpha + \beta S_y} e^{\epsilon_y^r} \tag{A.1}$$

$$\epsilon_1^r \sim N(0, \sigma_r^2) \tag{A.2}$$

$$\epsilon_y^r = \tau_y^r + \kappa_r \epsilon_{y-1}^r \tag{A.3}$$

$$\tau_y^r \sim N(0, \sigma_r^2) \tag{A.4}$$

$$N_{y+1,a+1} = N_{y,a} e^{-M_a}(1 - u_y v_a) \tag{A.5}$$

$$\begin{aligned} N_{y+1,a\text{max}} = {} & N_{y,a\text{max}-1} e^{-M_{a\text{max}-1}}(1 - u_y v_{a\text{max}-1}) \\ & + N_{y,a\text{max}} e^{-M_{a\text{max}}}(1 - u_y v_{a\text{max}}) \end{aligned} \tag{A.6}$$

$$u_y = \frac{C_y}{B_y} \tag{A.7}$$

$$B_y = \sum_a N_{y,a} v_a w_a \tag{A.8}$$

Recruitment Parameters

The underlying recruitment follows a Beverton−Holt stock−recruitment relationship formulated with a steepness parameter that determines recruitment as a proportion of virgin recruitment when the population is at 20% of the virgin biomass (Hilborn and Walters 1992).

$$\alpha = \text{SBPR}_0 \left(1 - \frac{z - 0.2}{0.8z}\right) \tag{A.9}$$

$$\beta = \frac{z - 0.2}{0.8 z R_0} \tag{A.10}$$

$$\text{SBPR}_0 = \sum_a P_{0,a} m_a f_a \tag{A.11}$$

$$R_0 = \frac{S_0}{\text{SBPR}_0} \tag{A.12}$$

TABLE A.2.—State, random, and intermediate variables.

Variable	Description
$N_{y,a}$	Numbers at the start of year y in age-class a
S_y	Spawning biomass in year y
S_0	Spawning biomass in an unfished population (virgin spawning biomass)
α	Parameter of the Beverton–Holt stock–recruitment relationship
β	Parameter of the Beverton–Holt stock–recruitment relationship
ϵ_y^r	Recruitment anomaly in year y
τ_y^r	Random component of the recruitment anomaly in year y
u^*	Exploitation rate modified by the 40:10 rule
U_y	Exploitation rate in year y
SBPR_0	Spawning biomass per recruit in a unfished population
$P_{0,a}$	Proportion of recruits alive at age a in an unfished population
R_{init}	Recruitment used to define the initial population
u_{init}	Exploitation rate used to define the initial population
$\text{SBPR}_{\text{init}}$	Spawning biomass per recruit in the initial population
$P_{\text{init},a}$	The proportion of recruits alive at age a in the initial population
C_y	Catch in year y
C'_y	Intermediate calculation for catch in year y when the catch is a function of the previous catch
B_y	Biomass in year y
$\hat{B}_y$	Biomass in year y estimated by the survey or stock assessment
ϵ_y^B	Biomass estimate anomaly in year y
τ_y^B	Random component of the biomass estimate anomaly in year y
ϵ_y^C	Harvest policy implementation error

$$P_{0,1} = 1 \tag{A.13}$$

$$P_{0,a+1} = P_{0,a}e^{-M_a} \tag{A.14}$$

$$P_{0,a\max} = \frac{P_{0,a\max-1}e^{-M_{a\max-1}}}{1 - e^{-M_{a\max}}} \tag{A.15}$$

$$S_y = \sum_a N_a m_a f_a \tag{A.16}$$

Initial Conditions

The population starts with a specified spawning biomass. The population is assumed to be in equilibrium with respect to the initial exploitation rate, and recruitment is constant. The initial exploitation rate is estimated to give the specified population size, and recruitment is calculated from the stock−recruitment relationship.

$$N_{1,1} = R_{\text{init}} \tag{A.17}$$

$$N_{1,a+1} = N_{1,a}e^{-M_a}(1 - u_{\text{init}}v_a) \tag{A.18}$$

$$N_{1,a\max} = \frac{N_{1,a\max-1}e^{-M_{a\max-1}}(1 - u_{\text{init}}v_{a\max-1})}{1 - e^{-M_{a\max}}(1 - u_{\text{init}}v_{a\max})} \tag{A.19}$$

$$R_{\text{init}} = \frac{1}{\beta} - \frac{\alpha}{\beta \cdot \text{SBPR}_{\text{init}}} \quad \text{from} \tag{A.20}$$

$$R_{\text{init}} = \frac{R_{\text{init}}\text{SBPR}_{\text{init}}}{\alpha + \beta R_{\text{init}}\text{SBPR}_{\text{init}}} \tag{A.21}$$

$$\text{SBPR}_{\text{init}} = \sum_a P_{\text{init},a} m_a f_a \tag{A.22}$$

$$P_{\text{init},1} = 1 \tag{A.23}$$

$$P_{\text{init},a+1} = P_{\text{init},a}e^{-M_a}(1 - u_{\text{init}}v_a) \tag{A.24}$$

$$P_{\text{init},a\max} = \frac{P_{\text{init},a\max-1}e^{-M_{a\max-1}}(1 - u_{\text{init}}v_{a\max-1})}{1 - e^{-M_{a\max}}(1 - u_{\text{init}}v_{a\max})} \tag{A.25}$$

Management Policies

In the simulations, catch is calculated on the basis of a specific management policy. Both stock assessment and survey-based policies are investigated. The actual catch includes implementation error.

Policy 1: 40:10.—Catch is the target exploitation rate times the estimated biomass. The target exploitation rate is zero when the estimated stock is less than 10% of the virgin stock; it equals the reference point when the estimated stock is more than 40% of the virgin stock; and it increases linearly from zero to the reference point when the estimated stock is between 10% and 40% of the virgin stock.

$$C_y = \min[\max(u^*\hat{B}_y, 0), 0.8\hat{B}_y]e^{\epsilon_y^C}$$

$$u^* = \begin{cases} 0 & \text{if } \hat{B}_y < 0.1\hat{B}_0 \\ u_{\text{ref}} & \text{if } \hat{B}_y > 0.4\hat{B}_0 \end{cases}$$

$$C_y = (-0.0333 + u_{\text{ref}}0.333)0.4u_{\text{ref}}\hat{B}_0$$

$$\text{if } 0.1\hat{B}_0 > \hat{B}_y > 0.4\hat{B}_0 \tag{A.26}$$

Policy 2: Survey-based policy.—Catch is a combination of a linear function of the biomass estimated from the survey and the catch in the previous year. It is constrained so that it cannot be less than zero or more that 80% of the estimated biomass.

$$C'_y = \phi + \lambda \hat{B}_y \text{bias} \tag{A.27}$$

$$C_y = \min[C_{y-1}\text{cLag} + (1 - \text{cLag}) \times \max(C'_y, 0), 0.8\hat{B}_y]e^{\epsilon^C_y} \tag{A.28}$$

The catch is restricted so that it is less than the biomass

$$C_y \leq B_y \quad (\text{i.e. } u_y \leq 1). \tag{A.29}$$

In both cases, the estimated biomass is the real biomass plus an error term. The error term incorporates an autocorrelation term.

$$\hat{B}_y = B_y e^{\epsilon^B_y} \tag{A.30}$$

$$\epsilon^B_1 = \log_e\left(\frac{\hat{B}_1}{B_1}\right) \tag{A.31}$$

$$\epsilon^B_y = \tau^B_y + \kappa_B \epsilon^B_{y-1} \tag{A.32}$$

$$\tau^B_y \sim N(0, \sigma^2_B) \tag{A.33}$$

$$B_y = \sum_a N_a v_a w_a \tag{A.34}$$