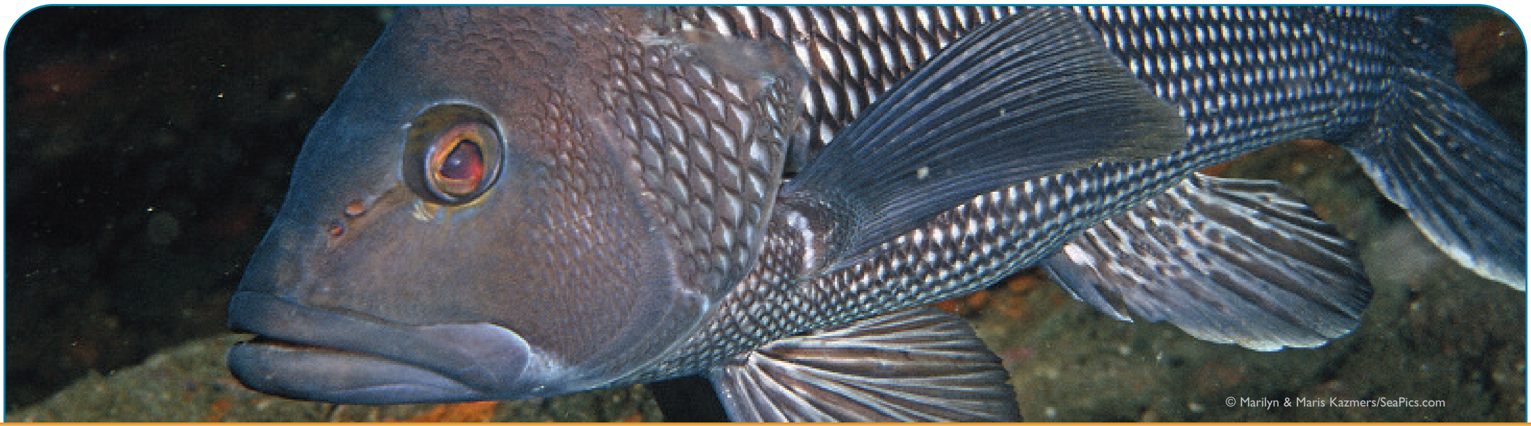

A REVIEW of REBUILDING PLANS for OVERFISHED STOCKS in the UNITED STATES

Identifying Situations of Special Concern

By

John Wiedenmann, MRAG Americas, Santa Cruz, CA

Dr. Marc Mangel, University of California, Santa Cruz

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Forward

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A policy-oriented synopsis of these research results is available at www.lenfestocean.org\publications. A scientific summary of the results has been submitted for publication and will be available, when published at www.lenfestocean.org\publications.

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Executive Summary

Our previous report (Phase I report: "An Evaluation of Rebuilding Plans for U.S. Fisheries", by Swasey, J. H. and Rosenberg, A. A., 2006) describes the first phase of a longer-term study of rebuilding plans in which an evaluation of the performance of rebuilding plans across the country is provided. The next phase of our study is an exploration of these plans in greater detail, to guide improvements in the planning process and in implementation of the management and policy steps taken to rebuild overfished stocks

Using traditional modeling methods from fishery science, we identify three situations of particular concern that may be overlooked in the rebuilding process:

1) Cases in which the stock is experiencing overfishing during the rebuilding period. In some instances, the biomass of a stock will still increase, but achieving the achieving the rebuilding target may require a severe dislocation of the fishery at some point in the future. Allowing overfishing during the during the rebuilding period also leaves little room for error, as it may stagnate or even prevent the rebuilding of a stock.

2) Cases in which stocks are considered rebuilt but the age distribution is far from the stable age distribution that would be associated with the life history parameters of the stock and the appropriate level of removal. In such situations, the stock may not be robust to removal and may fall below the rebuilding target within a decade.

3) Cases in which uncertainty is ignored in certain aspects of rebuilding trajectories. In such cases, rebuilding plans may be far too optimistic, or pessimistic, but the consequences of optimistic trajectories are more severe.

These cases are also illustrated with specific examples of stocks undergoing rebuilding, showing the potential impacts that they may have on all stocks requiring rebuilding.

1 Introduction

Our previous report (Phase I report: "An Evaluation of Rebuilding Plans for U.S. Fisheries", by Swasey, J. H. and Rosenberg, A. R., 2006) describes the first phase of a longer-term study of rebuilding plans in which an evaluation of the performance of rebuilding plans across the country is provided. The second phase of our study will is exploration of some of these plans in greater detail, to guide improvements in the planning process and in implementation of the management and policy steps taken to rebuild overfished stocks.

In the U.S., managers are mandated by the Sustainable Fisheries Act (1996) to create rebuilding plans that specify a timeline in which overfishing will end and the stocks will recover (Safina et al. 2005). Furthermore, the law requires that the plans are more likely to succeed than not, which is generally interpreted as a greater than 50% chance of success. There are currently 67 rebuilding plans for 74 federally managed stocks within U.S. waters that require rebuilding, with an additional 4 stocks experiencing overfishing and a reduction in fishing mortality is the required action. Some of the main conclusions from Swasey and Rosenberg (2006) are the following:

• Scientific data are lacking for many species, and this limits the development, implementation and success of rebuilding plans. Despite the statutory mandate to rebuild in as short as time as possible, not to exceed 10 years except under special circumstances, the actual rebuilding timeframes implemented have almost invariably been 10 years or longer.

• In some cases the clock has been reset to year one when the plans were revised, instead of utilizing the existing timeframe.

• Overfishing still occurs in 45% of stocks with rebuilding plans, with the notion that the rate of exploitation will be reduced 'some time in the future.' In many cases, there is a long lag between the start of the rebuilding plan and the reduction in fishing mortality.

• Monitoring rebuilding trajectories is essential to see if stocks are rebuilding as projected so that necessary revisions may be made to the plans. However, in the absence of monitoring, necessary revisions to the plans are not being made, inhibiting progress.

Our goal in this report is to identify situations of particular concern in the rebuilding process, from biological, policy or socio-economic perspectives. In general, for long-term effective management that involves substantial take, robust estimates of management reference points and current stock status are needed from stock assessment biologists (Brodziak and Legault 2005). The assessment process is well established, and most of the limitations of an assessment are the result of limited or inadequate data, rather than technical expertise.

Managers may deal with the information provided in the assessments and rebuilding analyses for particular species in different ways. For example, a rebuilding analysis for a given species may project future population levels under various management scenarios (see Punt et al. 2003 or Porch et al. 2003 for examples), and these scenarios may provide vastly different recovery timelines. Managers may choose to lean towards the resource and conservationist stakeholders, opting for the scenario that results in the greatest probability of recovery in the shortest amount of time. Or, they may choose to lean towards exploitationist stakeholders, opting for the scenario that results in the greatest allowable catch, while still enabling recovery within the rebuilding period. Where exactly on that continuum one should be is not a scientific question, although science can indicate if a stock is more likely than not to be able to recover under a given management plan. Furthermore, managers may choose to highlight certain aspects of the biology of the species (e.g. age distributions, strong year classes, alternate stable states, etc.) that may potentially impact the success of rebuilding.

We cannot determine the motivation of the individual rebuilding plans for the regional Management Councils, but certain trends are apparent in the way Councils act once it is determined that a species is in need of rebuilding. For example, the Caribbean Fishery Management Council (CFMC) has shut down the directed fisheries for all species undergoing rebuilding within U.S. waters in the region. Directed fisheries for three out of four stocks undergoing rebuilding managed by the North Pacific Fishery Management Council (NPFMC) are closed. Other regions have adopted similar strategies for specific stocks under their jurisdiction (e.g. Nassau and goliath grouper in both the South Atlantic and Gulf Fishery Management Councils). However, prohibiting harvest of overfished species is not practical for most species in most regions. As a result, most Councils allow for some level of removal, but this varies among Councils, as well as among species within a particular Council. For example, the New England Fishery Management Council (NEFMC) and the Mid-Atlantic Fishery Management Council (MAFMC) have set specific target fishing mortality rates for all years in the rebuilding timeframe for most species. Nearly all of the plans allow for overfishing within the first five years of rebuilding (Swasey and Rosenberg 2006 for more details). These councils are not the only ones to allow overfishing during rebuilding; they just specify the fishing mortality schedules in their rebuilding plans (Swasey and Rosenberg 2006).

In Section 2, we provide the conceptual foundations used in identifying the areas of particular concern. In Section 2.1, we define overfished, overfishing and rebuilt, and describe the ways in which management reference points that determine the status of a stock are estimated with different models. Many Councils allow for overfishing to occur during rebuilding and we show how this practice may still allow for a population to partially recover – but never rebuild as described by the law. We explain how "sustainable overfishing" can occur, why it is not an oxymoron and is a bad idea, and how it may vary for stocks of varying productivity. These explorations require a modest amount of mathematical modeling of fish population dynamics, which we introduce as needed, so that a reader unfamiliar with the field will be able to follow the essence of the arguments. In Section 2.1, we also explore the implications of age structure and of uncertainty that is a natural result of the stock assessment process. In particular, we show how ignoring various kinds of uncertainty may lead to rebuilding plans that are too optimistic.

In Section 2.2, we describe a variety of issues that may have serious implications for the rebuilding process. These range from the different levels of future fishing mortality set in the rebuilding plans to biological aspects of the species such as the age distribution of the population due to strong recruitment events.

We explain all of the ideas in Section 2 with conceptual models to show how they may impact the rebuilding process. In Section 3, we explore these ideas in greater detail, providing examples of stocks undergoing rebuilding that clearly illustrate them. In Section 3.1 we explore the impacts of allowing overfishing during rebuilding. We use summer flounder, South Atlantic (SA) black sea bass, snowy grouper and SA golden tilefish as examples to highlight the potential decreases in landings resulting from allowing overfishing during the rebuilding period. We also use Georges Bank (GB) cod, Gulf of Maine (GOM) cod, Southern New England/Mid-Atlantic (SNE/MA) yellowtail flounder and SNE/MA winter flounder as examples of how overfishing might slow a stock's recovery. In Section 3.2 we explore the impact of a skewed age distribution on stock recovery, using GB haddock and Pacific hake as examples. Finally, in Section 3.3 we highlight the impact that uncertainty has on rebuilding trajectories using GB yellowtail flounder and Cape Cod/Gulf of Maine (CC/GOM) yellowtail flounder as examples.

In Section 4 we draw some general conclusions about the areas of particular concern and their potential impacts on the rebuilding of depleted fisheries.

2 Conceptual Foundations

2.1 Management Reference Points, Sustainable Overfishing and Uncertainty

The population dynamics of all species result from changes in the per-capita population growth rate in time with respect to population size (Sibly et al. 2004). Renewable resource management is based on the notion of density dependence: the rate of growth of the population increases from low to intermediate population levels until it is maximized at some population size, after which the growth rate decreases until the population reaches its maximum size and growth stops (Figure 1).

In principle, if a harvested population was maintained at a level where its growth rate is maximized, and if the biomass harvested equals the biomass produced, then the population will remain in a steady state. In fisheries, this concept is referred to as the Maximum Sustainable Yield (MSY) and the population size (measured in biomass, B) where growth is maximized is called B_{MSY}. In his classic work, Ricker (1975) defined MSY in this manner (also see Mangel et al. 2002 for elaborations):

> MAXIMUM SUSTAINABLE YIELD (MSY OR Y_S): The largest average catch or yield that can continuously be taken from a stock under existing environmental conditions. (For species with fluctuating recruitment, the maximum might be obtained by taking fewer fish in some years than in others.) Also called: maximum equilibrium catch (MEC); maximum sustained yield; sustainable catch.

These definitions form the basis for many of the reference points used to determine if a stock is overfished or experiencing overfishing. A population is considered overfished when the biomass falls below some threshold set below B_{MSY}, often (but not always) 50% of B_{MSY}. A population is considered rebuilt when the population biomass reaches or exceeds B_{MSY}. For a population to be experiencing overfishing, the per unit biomass rate of removal, or fishing mortality, F, must exceed the level of fishing mortality that produces MSY, also known as F_{MSY}. These management reference points are derived from various population models, and although many different models have been developed, they generally fall into two categories: production models and age-structured models. We now describe these, which are well established in fisheries science (see Beverton and Holt 1957, Hilborn and Walters 1992, Quinn and Deriso 1999, and Haddon 2001 for more on the foundation of these models), using the minimum amount of mathematical modeling needed.

Production Models

Production models treat fish populations as biomass (without any other kind of structure such as age or sex) that changes with time. Although the use of production models for stock assessment has been questioned (Maunder 2003), we use them here because their simplicity allows one to understand the important concepts behind fisheries reference points. In a production model, the biomass level at the next time (B_{t+1}) is determined by the current biomass (B_t), the growth in biomass that will occur between times t and t+1, $G(B_t)$, and catch between t and t+1 (C_t). This relationship is represented by the balance equation (which can easily be implemented on a spreadsheet)

$$B_{t+1} = B_t + G(B_t) - C_t \tag{1}$$

A commonly used form for the production term is $G(B_t) = \frac{r}{p} B_t \left(1 - \left[\frac{B_t}{K} \right]^p \right)$ where r is maximum per capita productivity (or productivity at low population size), K is the population carrying capacity, and p determines the shape of the production curve. When p = 1, the growth curve is symmetrical (Figure 1) with maximum production occurring at 50% of carrying capacity so that. $B_{MSY} = \frac{K}{2}$. In this case, Eqn 1 is known as the Schaefer model; Smith (1994) has an excellent history of the early aspects of quantitative fishery science. If $p < 1$, the stock is more productive at smaller population sizes ($B_{MSY} < \frac{K}{2}$), thus shifting the production curve to the left (Figure 2a). When $p > 1$ the production curve shifts to the right, with $B_{MSY} > \frac{K}{2}$ (Figure 2a).

It is clear in Figure 2a that if r is held constant and p varies, not only does the curve shift, but MSY and the amount of production at a given biomass also change. To normalize comparisons, we note the MSY for $G(B_t) = \frac{r}{p} B_t \left(1 - \left[\frac{B_t}{K} \right]^p \right)$ is

$$MSY = \frac{rK}{(1+p)^{\left(\frac{1}{p}+1\right)}} \qquad (2)$$

and this allows one to choose r so that production curves with different values of p have the same maximum production (Figure 2b).

To estimate F_{MSY}, we first define the relationship between yield at any level of biomass, Y(B), and the fishing mortality rate (per unit biomass per year), F, according to

$$Y(B) = B(1 - e^{-F}) \tag{3}$$

When F is not too large, $1 - e^{-F} \approx F$ so that Y(B) is approximately F•B.

Equation 3 shows that at any level of biomass, a sustainable yield (catch = growth) can theoretically be removed from the population, keeping it in a steady state. This sustainable yield ($Y_S(B)$) is calculated from the production function when the biomass is B

$$Y_s(B) = \frac{r}{p} B \left(1 - \left[\frac{B}{K} \right]^p \right) \tag{4}$$

Thus, the fishing mortality rate $F_S(B)$ that produces the sustainable yield $Y_S(B)$ is estimated by substituting (3) into (4) and solving for F

$$F_S(B) = -\ln \left[1 - \frac{\frac{r}{p}\left(1 - \left(\frac{B}{K} \right)^p \right)}{B} \right] \tag{5}$$

The results of these calculations are illustrated in Figure 3a, using the approximation $1 - e^{-F} \approx F$ to allow us to draw straight lines. If the population is at $B_{MSY,}$ then $Y_S(B)$ = MSY, and $F_S(B) = F_{MSY}$. When the population is below B_{MSY}, $F_S(B)$ values are greater than

F_{MSY} (Figure 3a). By definition, $F > F_{MSY}$ is overfishing, but since $F_S(B)$ produces a catch equal to the growth, the result is a steady state for the population below B_{MSY} (Figure 3b). For a given population size, an F below $F_S(B)$ will result in population growth (Figure 3a). We thus reach an important conclusion*: if biomass is sufficiently low, a population experiencing overfishing may still increase, giving the illusion of good management practice.*

To facilitate comparisons among populations, values of F and B are often standardized by dividing them by F_{MSY} and B_{MSY}, respectively. These standardized values are referred to as "Ratios," and an F-Ratio = $F/F_{MSY} > 1$ indicates overfishing, and a B-Ratio = $B/B_{MSY} < 1$ indicates a population below the threshold for rebuilding (recall that the overfished threshold is some level below B_{MSY}). In Figure 3b, we show the biomass trajectories for a stock starting at 10% of carrying capacity and experiencing different F-ratios.

In Figure 4, we show sustainable F-Ratios, given different B-Ratios for the different production curves shown in Figure 4. For all variations of the model, if the population is below B_{MSY}, overfishing can occur and the population may remain stable or increase. Any F-Ratio below the lines in Figure 4 results in an increase in the size of the population. As the production curve shifts to the left, a much greater level of fishing mortality can be sustained when $B < B_{MSY}$. However, if the population is above B_{MSY}, then the sustainable F-Ratio declines dramatically. Alternatively, if the production curve is shifted to the right, then the population cannot sustain high levels of overfishing when $B < B_{MSY}$, but the sustainable F-Ratio decreases more gradually as $B > B_{MSY}$. Thus, it may be important to consider the shape of the production curve (if it can be determined) when setting future catch levels, since the population size where a stock is most productive will influence the amount of fishing mortality that can be sustained.

Peerhaps the easiest way to understand how these results is to think of F as the proportion of the total stock biomass caught during some time period, or $F \approx C_t/B_t$ (recall that this relationship holds true when F is small, but precise values of F are calculated using Eqn 5). If we examine the production curves shown in Figures 1 and 3a, we see that a MSY of 1250 is produced by a B_{MSY} of 5000. In other words, the per-capita production at B_{MSY} is 0.25 (MSY/B_{MSY}). If we think of F as the proportion of the stock removed, then the F that produces MSY would also be 0.25. Although for $B < B_{MSY}$ the total production is lower than MSY, the per-capita production is higher. At a B of 2500, the production is 937.5, translating to a per-capita production of 0.375, and any per-capita removal below 0.375 will result in population growth. If per-capita removal is greater than 0.25, then F will be greater than F_{MSY}, and overfishing will be occurring.

Beyond the Production Model: Adding Age-Structure

Typically, the first and most general extension of a production model is one that includes age dependence in key features of the life history of the species, such as size, fecundity, and mortality. These models can be very complex, and require much more data to fit the model than production models. To be able to fully deal with these issues, requires very high levels of technical expertise. As in the previous section, our goal here is to give the simplest introduction that will allow the reader to understand the salient points about species of particular concern.

With age-structured models, the population metric of interest is typically the spawning stock biomass, denoted by SSB. Generating a production curve and estimating management reference points (SSB_{MSY} and F_{MSY}) is more complicated than the calculation for production models. For the example given here, we incorporate variables characterizing the fraction of fish that are reproductively mature at age a (f_a), the fraction of fish of age a that are vulnerable to the fishery (s_a), and weight of a fish at age a (w_a). The exact models used to generate these age-specific variables are not important for our purposes here; they are all S-shaped, increasing with age until reaching a limiting value (see Haddon (2001) for other examples and details).

The number of individuals reaching a given age (a) at time $t+1$, $N_{t+1,a}$, is calculated according to

$$N_{t+1,a} = \begin{cases} R & \text{if } a = 1 \\ N_{t,a-1} e^{-(M_{a-1} + s_{a-1} F)} & \text{if } 1 < a < x \\ N_{t,x} e^{-(M_x + s_x F)} + N_{t,x-1} e^{-(M_{x-1} + s_{x-1} F)} & \text{if } a = x \end{cases} \quad (6)$$

where $e^{-(M_{a-1} + s_{a-1} F)}$ is the fraction of fish of age a-1 that survive to age a, x is the last age group specified (8 for this example), M_a is the natural mortality rate at age a (set to 0.2 for all ages for this example), and R is recruitment to the population.

Recruitment to the population may depend upon the spawning stock biomass at time t, $SSB_t = \sum_{a=1}^{x} w_a N_{t,a} f_a$, or it may depend on total egg production $E_t = \sum_{a=1}^{x} e_a w_a N_{t,a} f_a$, where e_a is the egg production per-unit spawning biomass. One may also wish to include some measure of egg quality, q_a, such that $E_t = \sum_{a=1}^{x} q_a e_a w_a N_{t,a} f_a$; for example, older spawners may produce more viable eggs and larvae for some species (Berkeley et al 2004; Scott et al. 2006). A functional form commonly used to described recruitment is one due to Beverton and Holt (1957); also see Quinn and Deriso (1999). Using spawning stock biomass as the determinant of recruitment, it is

$$R_{t+1} = \frac{\alpha \cdot SSB_t}{\beta + SSB_t} \quad (7)$$

where α is the maximum recruitment per unit biomass and β is a measure of the strength of density dependence (in this case the SSB that produces half the maximum recruitment). In this equation, recruitment is assumed to be at age-1. For recruitment that is related to egg production, SSB_t is replaced by E_t in Eqn 7.

Equations 6 and 7 are easily implemented on desktop computers. Before discussing the appropriate fishery metrics, we discuss one important property of the solutions of these equations.

In general, after a sufficiently long period of time, the solution of Eqns 6 and 7 will settle into the 'stable age distribution' (SAD) in which the fraction of individuals in a particular age class only depends upon age and not upon time (Figures 5a and 5b). When F=0, the stable age distribution describes the natural state of the fish population, and the other age distributions represent the perturbations due to fishing.

As fishing mortality increases, the age distribution shifts, with the younger age classes comprising a greater proportion of the total population (Figure 5a). The age distribution can also shift by changing the selectivity of the fishery. Lowering the age of selectivity (by decreasing mesh size, for example) will increase the proportion of younger age classes in the population (Figure 5b). On the other hand, increasing the age of selectivity will increase the proportion of older age classes in the population.

For age structured populations, two common management reference points are the yield-per-recruit (YPR) and spawner biomass-per-recruit (SPR). These are computed from Eqn 6 by fixing R to be a constant (the initial size of the cohort) and following the fate of the cohort in time. That is, we replace Eqn 6 by the simpler form

$$N_{a+1} = \begin{cases} R & \text{if } a=1 \\ N_{a-1}e^{-(M_{a-1}+s_{a-1}F)} & \text{if } 1<a<x \\ N_x e^{-(M_x+s_xF)} + N_{x-1}e^{-(M_{x-1}+s_{x-1}F)} & \text{if } a=x \end{cases} \qquad \text{(6a)}$$

In Eqn 6a, and in the calculation of YPR and SPR described below, recruitment is assumed to be at age-1, but this is not always the case, and these calculations can be easily modified for different ages at recruitment. Yield-per-recruit is the average expected yield to the fishery (in weight) from a single cohort. It is given by

$$YPR = \frac{1}{R}\sum_{a=1}^{x} w_a N_a \left(\frac{s_a F}{M + s_a F}\left(1 - e^{-(M_a + s_a F)}\right)\right) \qquad \text{(8a)}$$

Typically, one plots YPR as a function of fishing mortality rate F, as in Figure 6. In many cases, a management strategy is to choose the fishing mortality rate that gives a slope of the line tangent to the curve that is 0.X times the slope of the tangent line at the origin. Such plans are often referred to as "$F_{0.X}$" management plans. An "$F_{0.X}$" is useful because one does not need to know stock-recruitment relationships, and because that some $F_{0.X}$ values (such as $F_{0.1}$) may be reasonable approximations of F_{MSY} (Clark 1991; Figure 6 here).

The second metric, SPR, is the expected average weight that a given recruit from a cohort will reach in its lifetime, given different levels of fishing mortality. It is calculated according to

$$SPR = \frac{1}{R}\sum_{a=1}^{x} m_a w_a N_a \qquad (8b)$$

Unlike yield per recruit, SPR is always a declining function of fishing mortality rate (Figure 7). Many management plans are denoted by X% SPR, in which the fishing mortality rate is chosen so that the spawning biomass per recruit is X% (typically 40-60%, see below) of the SPR in the absence of fishing.

Although all of the details are more complicated, we can construct F-Ratio/B-Ratio plots for age-structured models that are analogous to Figure 4. In Figure 8, we show the relationship between the B-Ratio and sustainable F-Ratio for three levels of maximum per capita recruitment when the density-dependent parameter is held constant. As with the simpler production model, when the SSB moves below the level that produces MSY, the stock is able to sustain certain levels of overfishing. Theoretically, the farther below SSB_{MSY} the population goes, the greater level of overfishing it can sustain. That is, based on the population dynamics model outlined above, populations are more productive at lower stock sizes, and may therefore be able to sustain a higher fraction of removal. Changing maximum per capita recruitment causes small changes in the sustainable F-Ratios, although the more productive stocks can sustain slightly higher fishing mortality rates at lower biomass levels, but lower rates at higher biomass levels. For larger deviations in maximum per capita recruitment, the differences are minimal.

Thus, both age-structured and production models show that a population can, in principle, grow while experiencing overfishing. However, overfishing during the rebuilding period is simply a bad idea. First, the population will never rebuild to the desired target. Second, there is often a great deal of variability in the surplus production for a given level of biomass, or in the number of recruits produced per unit spawning biomass. The models described above assume that production is density-dependent (i.e. production only varies with stock size). However, density-independent factors, such as food availability, may have large influences on recruitment success (and therefore production), which may result in production being unrelated to stock size. In addition, a stock may actually be less productive at low biomass levels, a phenomenon known as depensation or an Allee effect (Myers et al. 1995). Depensation may occur if a stock is driven to sufficiently low levels where mating success is reduced, which may prevent a stock from recovering (Hutchings and Reynolds 2004). As a result, if a stock is less productive than assumed at low levels, allowing overfishing to occur during the rebuilding period may worsen the status of the stock, and thus lengthen, or even prevent, the rebuilding of a particular stock.

Uncertainty

In fisheries, many sources of uncertainty in stock assessment and management have been recognized (Rosenberg and Restrepo 1994; Francis and Shotton 1997, Hilborn and Mangel 1997). Some of the major types of uncertainty encountered are observation, process, model, and implementation uncertainty (Francis and Shotton 1997). Process uncertainty is due to the natural variability and is inherent to the system being studied (Ferson and Ginzburg 1996). Observation uncertainty and model uncertainty are both due to limited information and are properties of the analyst. Specifically, observation uncertainty results from the collection of data through sampling and measurement error (Hilborn and Mangel 1997), while model uncertainty is the result of incomplete information about the system dynamics (Francis and Shotton 1997). The "model" can be qualitative, such as the perceived geographic boundary of a stock, or it can be quantitative, such as assuming a particular parameter value or a particular model structure. Both model and observation uncertainty are very similar, and model uncertainty is often the result of observation uncertainty. Therefore, throughout this document we use the term observation uncertainty to mean uncertainty resulting from limited or incorrect information (either from data collection or model assumptions), that may be reduced through further observations. The final type of uncertainty is implementation uncertainty, which is the uncertainty about the extent to which management measures will be implemented successfully (Francis and Shotton 1997). For example, gear restrictions or quotas that are implemented to reduce harvest rate may not be successful at achieving a particular harvest rate.

Regardless of the type of uncertainty (and more will be said about that below), recognition of uncertainty forces us to think in terms of probabilities of different outcomes, rather than single outcomes. As described above, the Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA) requires that a rebuilding plan must specify a time period for rebuilding, and must be more likely than not to succeed, which is generally interpreted to mean at least a 50% chance of rebuilding in a specified time frame. In consequence, a common framework for characterizing rebuilding is that the probability that the stock has achieved a certain size by a given time exceeds a specified rebuilding threshold. For example, we may write $\Pr\{\text{recovery by } t\} > 0.5$ to signify that the probability that the stock has crossed a building threshold by time t is greater than 50%.

Process and observation uncertainty are often treated identically, but they are not interchangeable since they represent the difference between variation in the biology of the system and variation in our measurement of the biology. That is, the difference is between a fixed but unknown parameter (observation uncertainty) and random fluctuations around a fixed value (process uncertainty).

We illustrate this difference, and its implications, using a model originally conceived to understand population growth in a fluctuating environment (Lewontin and Cohen 1969). In this model, population size changes due to a deterministic term, $(1+r)$, characterizing recovery and a random term with intensity D characterizing fluctuations according to

$$X(t+1) = (1+r)X(t) + \sqrt{2D}\xi(t) \quad (9)$$

where X(t) the logarithm of population size (we ignore density dependence and $\xi(t)$ is a normally distributed random variable with mean 0 and variance 1; it is the classic bell-shaped curve, peaked at 0 (and we write $\xi(t) \sim N(0,1)$ to indicate this). There is a large literature concerning such models; one recent source is Lande et al. (2003). If only process uncertainty is assumed, then it is straightforward to compute the probability of recovery by time t assuming that r is known from prior measurements of population size (Crank 1985). In particular, r is the slope of a plot of the logarithm of population size against time and D is a measure of the variance around that relationship, The result of such a calculation leads to a curve such as the one shown in Figure 9. In this sample case, we conclude that the minimum time for recovery with 50% probability is 30 years.

Including observation uncertainty changes the results profoundly. By recognizing that the parameter characterizing the deterministic component of the dynamics is fixed by biology but uncertain, we also recognize that our estimate of it should not be characterized by a single value of r with fluctuations around that value. Instead, the estimate should be characterized by a family of fixed values of r, each with an associated probability of being the true but unknown biological parameter and with fluctuations around each of those values. In that case, we should generate not a single curve but a family of such curves (Figure 10).

Examining the 80% boundary curves in Figure 10 is illustrative. At 50% probability of recovery by time t, we see that the minimum time for recovery is about 20 years. Thus, had the species recovered more quickly than anticipated (20 rather than 30 years) and had observation uncertainty been ignored, one would conclude that management had been particularly good, whereas instead one was particularly lucky that the true value of the uncertain parameter was greater than the mean value. Similarly, the other 80% boundary predicts that recovery could take as long as 50 years; so that information indicating that the target of recovery by year 30 not being met would not necessarily suggest poor management, but that the uncertain but fixed parameter was smaller than the average value used. Thus, observation uncertainty may lead to rebuilding plans that are overly optimistic or pessimistic, but the consequences are more severe when rebuilding plans are based on optimistic projections. Furthermore, at year 30, we see that the 80% boundaries range from nearly 0 to 1, so that the assignment of a recovery probability of 50% by year 30 'on average' (as the regulatory mechanisms would provide) is essentially uninformative. This property, in fact, caused Ludwig (1999) to ask if it is meaningful to estimate the probability of extinction in conservation biology.

The impact that a rebuilding plan will have on a population is typically determined by projecting the population forward under the specific management plan. When doing this, some form of stochasticity is added to the model and the probability of recovering within the rebuilding timeframe is examined. For the production model, the stochasticity can be incorporated into any or all parameters, but is typically added by drawing the growth rate (r) from a distribution of values (often determined from the range of values presented in the assessment). For the models with age structure, process uncertainty or stochasticity is added to the recruitment function, either by drawing randomly from past recruitment levels, or by adding an error term to stock-recruit model. In particular, for computations we draw r from a normal distribution with a mean of 0.5 and standard deviation of 0.1(r ~ N(0.5, 0.1)). For the age-structured model, we added uncertainty to recruitment by multiplying the Beverton-Holt recruitment model by a random term so that $R_{t+1} = \frac{\alpha S_t}{\beta + S_t} e^{\xi_t}$, where

ξ_t ~ N(0, 0.25). This allows us to tabulate, in a series of simulations, the number of times the population size crosses the recovery threshold, and thus to determine the probability of recovery by a fixed time in the future. If the management measures added to the model (a set level of future F values) result in the probability of recovery being less than 50%, the measures must be changed until the threshold is reached.

This approach will allow us to deal with process uncertainty, but not observation uncertainty, for example in the parameters of the stock recruitment function. As an illustration of that uncertainty, in Figure 11 we show the data and estimated recruitment function for lingcod (Munch et al. 2005). Most stock-recruitment relationships assume that populations are closed. This requires that R=0 when S_t=0, as in Eqn 7. But often we do not know the stock recruitment relationship at small values of spawning stock size (the points in Figure 11) and this should be admitted (note how the 95% uncertainty bands in Figure 11 grow for small spawning stock sizes).

The X% SPR management strategies are a result of an attempt to deal with uncertainty in the form of the stock-recruitment relationship. Recognizing that we may never know the stock-recruitment relationship, Clark (1991) asked if a proxy involving a percentage of the SPR in the absence of fishing could be used to approximate F_{MSY}, under a variety of stock-recruitment relationships. The answer was a guarded yes, although we are still uncertain about the value of the percentage of the unfished SPR (see Clark 2002; MacCall 2002).

Given the various ways in which uncertainty can impact the rebuilding of a stock, the question remains: how can the information on uncertainty be used when trying to rebuild overfished stocks? First, observation uncertainty should be incorporated into the rebuilding analysis to produce a suite of rebuilding projections similar to those shown in Figure 10. If one wishes to err on the side of the resource, then it may be appropriate to use one of the more pessimistic projections, and set future quotas accordingly. In addition, it may be wise to focus management on whether or not the stock is above the rebuilding target at the current time, rather than on long-term time horizons.

2.2 Implications for Rebuilding

We now turn to the implications of our previous analyses for rebuilding and identifying situations of particular concern. To do this, we focus on two key factors: 1) the way in which fishing mortality is reduced and 2) the effects of age distributions that are far from the stable age distribution on our assessment of the status of the stock.

Schedules for Reducing Fishing Mortality Rates

Many of the Management Councils target future levels of fishing mortality in the rebuilding plans for depleted populations (Swasey and Rosenberg 2006). If a population is experiencing overfishing, then the current levels of fishing mortality must be reduced to a level that will allow for rebuilding within the timeline specified. As we have shown, a population that is below B_{MSY} (for a production model) or SSB_{MSY} (for an age structured model) may be able to withstand certain levels of overfishing and still increase in size. Although a population may grow while overfishing is occurring, for it to reach the rebuilding threshold, F must be reduced to a level below F_{MSY} during the rebuilding period. The way in which F is reduced during rebuilding varies by species and by council. Once a rebuilding plan is created, F may be immediately dropped below F_{MSY}, it may be gradually reduced over time, or it may be reduced in a stepwise manner (Figure 12).

Regardless of the manner in which F is reduced, one general rule holds: the higher the F-Ratio at the start, the more F must be reduced to enable rebuilding within a specified time frame. To illustrate this idea, we projected a population forward under a single reduction in F in the fifth year of the rebuilding plan. Given a 10 year rebuilding timeline, the F-Ratio is greater than 1 for the first five years and less than 1 for the final five years. In Figure 13, we show the percent decrease in the current F required to rebuild (rebuilding determined as 50% or more of model runs that result in population recovery; B_0 = 2500, r = 0.5, K = 10000) as a function of the F-Ratio for the first five years of rebuilding. This relationship is not linear however, a starting F that is 10% above F_{MSY} needs to be reduced by 21%, whereas a starting F that is 70% above F_{MSY} needs to be reduced by 63% to ensure a 50% or greater probability of recovery.

Keeping F constant for the first few years of rebuilding will allow for increased catches during this period, so long as the population is increasing. However, to achieve rebuilding, F must be reduced, which will result in a dramatic decrease in allowable catch level at some time in the future. Although such a plan may seem favorable at first due to the increasing quotas, it will likely be contested when quotas are greatly reduced to achieve rebuilding. In Figure 14, we show the catch levels for three different rebuilding strategies. In scenario 1, the F-Ratio = 1.3 for the first five years of rebuilding, then reduced to a level that will enable rebuilding (F-Ratio =0.6). The reduction in F results in a 46% decrease in allowable catch from year 5 to year 6. In scenario 2, F is gradually reduced (from a starting F-Ratio=1.44) to maintain a constant catch throughout rebuilding. In scenario 3, F is immediately dropped below F_{MSY} (F-Ratio = 0.85), and held constant throughout the rebuilding period. Each scenario has a nearly equal probability of recovery (0.52 for scenario 1, 0.51 for scenarios 2 and 3), and while scenarios 1 and 2 have nearly identical total catches for the entire period, scenario 3 results in a substantially higher total (approximately 17% more) without disruption of the fishery.

Age Structure

In general, recruitment fluctuates in the natural world and this means that the age structure of a population will fluctuate. This becomes important because the age structure of a population may greatly affect the probability of recovery. Strong recruitment events in particular years will cause the population biomass to increase dramatically as the recruited cohorts grow and mature. However, the cohorts will ultimately move out of the fishery, depending on the longevity of the species (Figure 15). If no additional strong recruitment events occur during this time period, then the population biomass will decline.

To illustrate this point, we use the age-structured model described previously, with rebuilding initiated in year 0, in which a larger than usual recruitment event occurs in year 1. In Figure 16, we show the result when there are no further fluctuations in recruitment. At year 10, the end of the rebuilding period, it appears that the stock has been rebuilt (although declining). Once the strong year class is gone from the population, the population SSB declines dramatically. At the end of the rebuilding period if quotas are set at MSY, since the strong year class is gone, the population biomass falls below the rebuilding threshold (SSB_{MSY}). Depending on the time between assessments, it may take years to realize that the population is unable to sustain such high exploitation rates, and the population may become overfished again. If left unchecked, taking MSY from the population each year will result in the reduction of SSB to 0 (Figure 16). Thus, strong recruitment events may actually mask faulty management measures. Treating a population as recovered when it is the result of a single year class may be very problematic, as the population may experience overfishing once the cohort is gone, resulting in a decline (cf. Aubone 2004).

As described above, after a sufficiently long period of time, a population will settle into the SAD in which the fraction of individuals in a particular age class remains constant through time. In the above example, the strong recruitment event results in a much higher fraction of the population in a particular year class, skewing the age distribution of the population. A population that is skewed towards younger age-classes means that a greater proportion of the population (in relation to the stable age distribution) is made up of young individuals. Conversely, a population skewed towards older age-classes means that there are more older individuals in the population relative to the stable distribution. Different mechanisms may result in a population being skewed in either direction. For example, we have already mentioned that fishing generally skews the age distribution of a stock towards the younger fish because more individuals from the older age classes are removed (Figure 5a). In comparison, a few strong recruitment events will also skew a population towards the younger age classes. However, as the cohorts age, the age distribution will begin to shift towards the older age classes.

Many factors may cause the age distribution of a stock to become skewed, from a rebuilding perspective, we particularly want to examine how a population that is skewed at the onset of “recovery” may affect its chances for long-term recovery. By recovery, we mean the rebuilding is completed and the SSB exceeds SSB_{MSY}. To examine the impact that a skewed age distribution may have on the prospect for long-term recovery (staying above SSB_{MSY}), we allow the age-structured population described above to reach its SAD under no fishing pressure. We then skew the age distribution of the stock that is considered rebuilt. That is, we start the population at a set SSB above SSB_{MSY}, but the fraction of the total SSB that falls into each age class differs from the stable age distribution. We then remove different levels of harvest (≤ MSY) from the population each year, and examine if the SSB falls below SSB_{MSY} within a 50 year timeframe. We assume that there is no stochasticity in recruitment. Although this assumption is overly simplistic (e.g., a skewed age distribution is likely the result of highly stochastic recruitment), adding stochasticity obscures the underlying relationship between a skewed age distribution and stock recovery.

There are many ways to estimate how skewed an age distribution is from the SAD, but the results can be best understood by considering the proportion of the spawning biomass that is made up of young spawners. For our model, full maturity (when all members of an age-class are mature) occurs at age 4. Therefore, we consider fish age-3 and younger to be "young" spawners and the proportion in the population is

$$\frac{SSB_1 + SSB_2 + SSB_3}{\sum_{a=1}^{8} SSB_a} \tag{11}$$

When the population is in the SAD, the proportion of young spawners is approximately 37%. As a result, proportions of young spawners less than 37% indicate that the SSB is comprised of a greater proportion of old spawners, and the age distribution is therefore skewed towards the older age-classes. Alternatively, proportions of young spawners in excess of 37% indicate a greater proportion of young spawners in the population and that the age distribution is skewed toward the younger age-classes. In Figure 17 we show how the proportion of young spawners in the population affects the long-term recovery for the population. If the population is heavily skewed toward the older age classes, these individuals quickly move out of the population, and the probability of SSB falling below SSB_{MSY} for a variety of harvest strategies (catch $\leq$ MSY) is very high. We show some specific population trajectories in Figure 18 to highlight the danger of not considering the age-structure of a population. If the population is in the SAD, then MSY can be removed and the population will remain above SSB_{MSY}. However, if the age-distribution is skewed (in this example towards older age classes), the removal of MSY may result in a population collapse in less than five years.

The results shown in Figure 17 depend upon a variety of the life history parameters characterizing the stock of interest, and not just the skew of the age distribution at the time of rebuilding relative to the SAD. For example, natural mortality, age at first reproduction and maximum lifespan can all have profound effects on the shape of the curves in Figure 17. For our model, we assume that recruitment is constant for a given level of SSB because egg production is proportional to biomass. In other words, the age composition of the SSB does not impact the resulting recruitment. However, this may not be the case. For example, there is evidence that suggests that for some species, maternal effects such as size or age at spawning may greatly impact recruitment (Murawski et al. 2001; Berkeley et al. 2004; Scott et al. 2006; Walsh et al. 2006). Older and larger members of a stock may produce more viable eggs and larvae, potentially resulting in strong recruitment events. Alternatively, smaller, younger fish may produce much less viable eggs and larvae, such that a population that contains mostly young spawners may experience successive recruitment failures.

To illustrate how maternal effects might affect the probability of long-term recovery, we alter the above model, making recruitment dependent upon egg production. In our model, egg production increases exponentially with fish size, so the older individuals produce dramatically more eggs. In addition, egg quality, q_a, increases with age, following an S-shaped curve, reaching a maximum at age 4. Instead of using SSB_{MSY} as our threshold, we use the level of egg production that produces MSY, or E_{MSY}. In Figure 19 we show how the young spawners in the population affect the long-term recovery for the population. As in our model ignoring age-specific egg production, if the population is heavily skewed toward the older age classes, these individuals quickly move out of the population, and the probability of egg production falling below E_{MSY} is very high for a variety of harvests (catch $\leq$ MSY). In addition, if the population is skewed towards the younger age-classes, then too few eggs of high quality are produced and the probability of egg production falling below E_{MSY} is also very high.

Although the shapes of the curves shown in these figures may vary greatly among stocks, the principle remains intact: if a stock is rebuilt with an age distribution that is far from the SAD, then it may not be able to sustain substantial harvest.

3 Case Studies

For Section 2 of this report, we adopted a modeling approach to identify areas of particular concern in the rebuilding process. Our goal was to highlight these situations so that colleagues could pay special attention to monitoring them. We now use examples of stocks undergoing rebuilding that highlight the areas of concern addressed in our Section 2.

In Figure 20, we provide a summary of the status of all stocks undergoing rebuilding in U.S. waters. This figure serves as a guide to anyone who wants to easily discover how a particular stock is doing with respect to biomass level, harvest rates and population trend. However, many of the classifications shown in Figure 20 are simply best estimates in data limited situations. Because data are limited for so many stocks, it was not possible to determine all the stocks that illustrated the areas of particular concern. Furthermore, these data limitations are more prominent in certain regions. As a result, we attempted to balance the examples from as many regions as possible, finding those that best illustrated our points.

The three main areas of concern identified in Section 2 that are explored in greater detail here are:

1) Cases in which overfishing occurs during the rebuilding process. In Section 3.1 we use summer flounder, South Atlantic (SA) black sea bass, snowy grouper and SA golden tilefish as examples to highlight the potential decreases in landings resulting from allowing overfishing during the rebuilding period. We also use Georges Bank (GB) cod, Gulf of Maine (GOM) cod, Southern New England / Mid-Atlantic (SNE/MA) yellowtail flounder and SNE/MA winter flounder as examples of how overfishing might slow a stock's recovery.

2) Cases in which stocks are considered rebuilt but the age distribution is far from the stable age distribution that would be associated with the life history parameters of the stock and the appropriate level of removal. In Section 3.2 we use GB haddock and Pacific hake as examples of stocks with skewed age distributions.

3) Cases in which uncertainty is ignored in some aspect of the computation and/or prediction of rebuilding trajectories. In Section 3.3 we use GB yellowtail flounder and CC/GOM yellowtail flounder to highlight the impact that uncertainty has on rebuilding trajectories.

3.1 Overfishing During Rebuilding

Previously, we showed how a stock that is sufficiently depleted can sustain overfishing and still increase in size. We also showed that a rebuilding plan for a stock can allow for overfishing for part of the rebuilding period and the stock may still recover in the specified timeline. However, depending on the level of overfishing allowed, a dramatic reduction in the F may be needed to achieve rebuilding. The higher the level of overfishing allowed, the greater the reduction in F that is likely to be needed to rebuild a given stock. However, overfishing during rebuilding is ill-advised for two reasons. First, if a dramatic decrease in F is needed, such a reduction in quotas may be fiercely contested by stakeholders, which may in turn hinder the rebuilding process. Second, allowing overfishing during the rebuilding period leaves little room for error. As we will show in Section 3.3, uncertainty in rebuilding projections may greatly impact the trajectories, ultimately influencing the predicted level of harvest that a stock can sustain. Overfishing a stock undergoing rebuilding may result in little or no recovery, and there are many cases where this has occurred.

In choosing stocks for this section we only considered stocks where overfishing is currently occurring and where the biomass trend is known. As classified in Figure 20, the stocks that are experiencing overfishing with increasing biomass trends are summer flounder, Atlantic sea scallop, monkfish (both north and south stocks), SA golden tilefish, GB cod, GOM cod, GB yellowtail flounder, SNE/MA yellowtail flounder, SNE/MA winter flounder, white hake and greater amberjack. Stocks that are experiencing overfishing with decreasing biomass trends are CC/GOM yellowtail flounder, SA black sea bass, snowy grouper and bluefin tuna. These are the stocks for which enough data are available to estimate trends in stock biomass. There are many more stocks undergoing rebuilding that are still being overfished, but with limited information on biomass trends. These stocks are Gulf red grouper, gag grouper, SA red snapper, SA red grouper, speckled hind, Warsaw grouper, SA black grouper, SA red drum, queen conch, Gulf red snapper, Gulf vermilion snapper, large coastal shark (LCS) complex, blue marlin, and white marlin (Figure 20).

There are some examples of stocks that have sustained population abundance while experiencing continued overfishing: Atlantic sea scallops, summer flounder, and greater amberjack. We did not select Atlantic sea scallop because they have been successfully rebuilt, and F has fluctuated around F_{MSY} in recent years. We also did not select greater amberjack because the data required to show how a stock can grow while being overfished are not explicitly provided in the most recent assessment (SEDAR/SAFMC 2005). Therefore, we selected summer flounder as our example of a stock that has steadily increased while experiencing overfishing.

We also wanted examples of stocks where dramatic reductions in landings were called for to end overfishing. Recent management measures by the South Atlantic Fishery

Management Council (SAFMC) have called for sharp decreases in landings for SA black sea bass, snowy grouper and SA golden tilefish (SAFMC 2005). As a result, we use these stocks as examples where dramatic reductions are required after allowing overfishing throughout the rebuilding period.

Of the stocks where overfishing is occurring and the biomass trend is known, many are the groundfish stocks under the jurisdiction of the New England Fishery Management Council (NEFMC; Figure 20). The rebuilding clock for most New England groundfish was reset in 2004 with Amendment 13, in part because management reference points were re-estimated in 2002 (NEFMC 2003), but largely because the Council had previously failed to prevent overfishing and develop rebuilding plans for many stocks that require them. In most cases, target F levels for individual stocks are to be gradually reduced from 2004 to 2014 (some stocks require longer rebuilding timelines). Amendment 13 calls for reductions in F to $F_{Rebuild}$ in 2009 for those stocks that can be rebuilt by 2014. The reduction in quota resulting from this decrease in F depends on the rebuilding progress of the stock and future F levels. Although we are not able determine if drastic reductions will occur, we do present the projected F levels and the actual values from the most recent assessment for GB and GOM cod, SNE/MA yellowtail flounder, SNE/MA winter flounder and white hake. We reserve discussion of GB and CC/GOM yellowtail flounder for our section on uncertainty.

Summer Flounder

Summer flounder have been overfished since at least 1982 (the first year used in the assessments), but population size has been gradually growing since 1990 while overfishing has occurred throughout the time series. To show how summer flounder have grown while experiencing overfishing, we rearrange Eqn 1, solving for population growth (or production)

$$G(B_t) = B_{t+1} - B_t + C_t \quad (12)$$

We estimated of B_{t+1}, B_t, and C_t from the 2003 stock assessment (Terceiro 2003) because the most recent assessment (NEFSC 2005a) does not provide explicit estimates of B. In Figure 21, we show the per-capita production ($G(B_t)/B_t$) and removal (C_t/B_t) for summer flounder from 1982 to 2001. It can be seen that in most years from 1990 onwards, production exceeded removal, even in the presence of overfishing, resulting in the gradual increase in stock biomass.

As we showed in Section 2.1, allowing overfishing during the rebuilding period may result in a dramatic dislocation to the fishery at a later time in order for the stock to rebuild. For summer flounder, the 2005 stock assessment revealed that stock biomass has crossed the overfished threshold of 1/2 B_{MSY} (NEFSC 2005a). Stochastic forecasts were conducted, incorporating uncertainty in 2005 stock size from survey variability, and assumed current discard to landings proportions. Projected landings in 2006 are 14,969 mt, providing a median F estimate in 2006 of 0.41 (F_{Ratio} = 1.57). A subsequent reduction in fishing mortality in 2007 to F = 0.26 is forecast to yield landings of 10,853 mt, a 28% reduction (Figure 22; NEFSC 2005a). If these target F levels are met, it is estimated that the stock will have a 50% chance or greater of rebuilding by 2008. Whether or not quotas will be set to achieve these target F levels remains to be seen.

Snowy Grouper

A rebuilding plan for snowy grouper was implemented in 1992 with a proposed rebuilding timeline of 15 years. The South Atlantic Fishery Management Council's (SAFMC) efforts to rebuild the stock included catch quotas, trip limits, recreational bag limits and the *Oculina* closed area (Swasey and Rosenberg 2006). Snowy grouper was last assessed in 2004

(SAFMC 2004), and suggest that past management measures implemented for rebuilding were ineffective, as the stock is severely depleted and overfishing has occurred since implementation of these measures. While a formal rebuilding plan is being developed for snowy grouper, the Council has developed and approved Amendment 13C to the Snapper/Grouper Fishery Management Plan (FMP) to end overfishing. Amendment 13C will reduce the commercial quota from approximately 184.4 mt to 80.8 mt in year 1, to 63 mt in year 2 and finally to 44.9 mt in year 3 (Figure 23; SAFMC 2005). This drop represents a 76% decrease in the quota for snowy grouper.

South Atlantic Black Sea Bass

A 10-year rebuilding period for SA black sea bass began in 1999. However, the rebuilding plan was based on management reference points that have now been shown to be greatly exaggerated, and the Council decided that previously implemented management measures (gear restrictions and size limits) would be sufficient to rebuild the stock within this timeframe based on the revised reference points (Swasey and Rosenberg 2006). The stock was last assessed in 2003 and it was still overfished and experiencing overfishing (SAFMC 2003). Stochastic projections under various natural mortality and recruitment parameterizations indicate that the stock may take between 10 to 25 years to rebuild, provided that F is greatly reduced (by as much 84%) at the start of the rebuilding period. To end overfishing, Amendment 13C establishes a total allowable catch (TAC) of 594.4 mt (gutted weight) in year 1, 526.3 mt in year 2, and 384.3 mt in year 3 to be divided among the recreational and commercial fisheries (SAFMC 2005). Landings in 2003 were approximately 630 mt (SAMFC 2003), so the TAC in year 3 represents a 39% reduction in the landings from 2003 (Figure 24). It is unclear if the TAC proposed in Amendment 13C will enable rebuilding within the timeline estimated in the last assessment, as the decrease in landings is not as dramatic as the decrease in F required to rebuild.

South Atlantic Golden Tilefish

Along with SA black sea bass and snowy grouper, Amendment 13C calls for a dramatic reduction in the quota for SA golden tilefish (SAFMC 2005). The latest assessment for SA golden tilefish indicates that the stock is not overfished, but that overfishing is occurring (SAFMC 2004). As a result, no rebuilding schedule for SA golden tilefish has been identified, but the Council aims to quickly end overfishing with the Amendment 13C (Swasey and Rosenberg 2006). Amendment 13C calls for a reduction in the commercial quota from 509 mt to 150.1 mt, a 70.5% reduction, and set a bag limit for the recreational fishery (SAFMC 2005). In Figure 25,m we show SA golden tilefish landings from 1984 to 2002, along with the quota established in Amendment 13C. Landings in 2002 were only 194 mt compared to the 509 mt quota. Therefore, the new quota of 150.1 mt is a 22.6% decrease in the 2002 landings (the most recent available estimate of landings).

After years of ineffective regulations aimed at reducing F for overfished stocks, the SAFMC has taken a dramatic step towards ending overfishing for many stocks (snowy grouper, SA black sea bass and SA golden tilefish described above, as well as red porgy and vermillion snapper) with the passage of Amendment 13C. It remains to be seen whether or not the reductions in quotas specified by Amendment 13C will end overfishing of these stocks, because the F that corresponds to these reductions is not stated. Nevertheless, dramatically reducing (or setting) a quota for an overfished stock is the first and most important step towards successful rebuilding.

New England Groundfish

The groundfish stocks from the New England region undergoing rebuilding that are currently being overfished are GB and GOM cod, GB, SNE/MA and CC/GOM yellowtail flounder, SNE/MA winter flounder and white hake (Figure 20). The rebuilding clock for most groundfish stocks undergoing rebuilding was reset in 2004, along with new target F levels (NEFMC 2003): Target F levels are now from 2004 on, with most stocks rebuilding by 2014. Of the stocks we mention here, only GB cod and CC/GOM yellowtail flounder require rebuilding timelines greater than 10 years, with both stocks requiring an estimated 20 years (by 2024). Projections were based on results from the 2002 assessment for all groundfish stocks (NEFMC 2003), which estimated stock status to 2001. As a result, the projections used assumed F values for 2002 and 2003 to estimate the target F from 2004 on. Because the groundfish stocks were reassessed in 2005 (estimating stock status to 2004), we can compare the assumed values for 2002 and 2003, and target value for 2004 to those estimated in the assessment. Amendment 13, to the Northeast Groundfish FMP, also provides total allowable catch (TAC) for each stock from 2004 to 2006, so we are able compare these target TACs to the observed landings and discards (NEFMC 2003). In Figures 26a-26e we compare the assumed and target F levels for 2002-2004 from NEFMC (2003) to those estimated in NEFSC (2005b) for GB cod, GOM cod, SNE/MA yellowtail flounder, SNE/MA winter and white hake, respectively. Also, in Table 1 we compare target and actual F levels with the projected $F_{Rebuild}$ as well as compare target and actual landings for 2004. In nearly all years for these stocks, the actual F was higher than the F levels used in the projections, with only the 2003 assumed F for GB cod and SNE/MA yellowtail flounder higher than the actual values (Figures 26a-26e). Exceeding the target F is an example of implementation uncertainty, and it can occur if landings exceed the proposed TAC in a year, if actual biomass is lower than the assumed level, or if the stock has been less productive than predicted. In 2004, the landings for GB and GOM cod were greater than the TACs proposed in Amendment 13, while the landings for SNE/MA yellowtail flounder, SNE/MA winter flounder and white hake were less than the proposed TACs (Table

1). In section Section 3.3, we discuss some of these factors in greater detail, using GB and CC/GOM yellowtail as examples.

To examine how the higher F levels from 2002 to 2004 may impact rebuilding trajectories, we can project the population from 2005 to the end of the rebuilding period using abundance at age data for 2004 obtained from NEFSC (2005b), and target F levels from the rebuilding plan for each stock (NEFMC 2003). We constructed projections for GB cod, GOM cod, SNE/MA yellowtail flounder and SNE/MA winter flounder. All but GB cod have an end date of 2014, with GB cod requiring an extra 10 years to rebuild by 2024 (NEFMC 2003).

To project forward,, we added stochasticity to recruitment, either by drawing randomly from past recruitment levels, or by adding an error term to a stock-recruit model. Specifically, we use the Beverton-Holt recruitment model, $R_{t+1} = \frac{\alpha S_t}{\beta + S_t} e^{\xi_t}$, where ξ_t characterizes fluctuations in recruitment. For GOM cod, we obtained estimates of *a*, *b* and ξ_t from NEFSC (2002b). Although estimates of α, β and ξ_t are presented for the other stocks, different parameterizations of the Beverton-Holt model were used, and the exact form of the model is not always clear. Therefore, we estimated α, β and ξ_t for GB cod, SNE/MA yellowtail flounder and SNE/MA winter flounder based on stock-recruit data presented in NEFSC (2005b). We found it more difficult to obtain reliable parameter estimates for GB cod and SNE/MA yellowtail flounder, so we incorporated recruitment stochasticity into the projections by drawing randomly from past recruitment levels.

Stock projections for GB cod, GOM cod, SNE/MA yellowtail flounder and SNE/MA winter flounder are shown in Figures 27a-27d, respectively. Based on our projections, only GB cod is still on track to rebuild by the end of its rebuilding period. In fact, our projection indicates a 77% chance of rebuilding by 2024 (Figure 27a). Not surprisingly, only GB cod had a higher estimate of SSB in 2004 than predicted and actual F values close to predictions in Amendment 13 (Figure 26a; NEFSC 2005b). Estimates of SSB for GOM cod, SNE/MA yellowtail flounder and SNE/MA winter flounder in 2004 were lower than predicted while estimates of F were significantly higher than predicted in Amendment 13 (Figures 26b, 26c, and 26d; NEFSC 2005b). It is not surprising then that our projections suggest that these stocks may be less likely to rebuild by 2014, with approximately 15, 0.5 and 7.8% chance of rebuilding by 2014 for GOM cod, SNE/MA yellowtail flounder and SNE/MA winter flounder, respectively (Figure 27b; Figure 27c; Figure 27d). However, these projections are rough approximations at best because we use different parameterizations for recruitment. Even though the projections are not exact and contain much uncertainty, they suggest that rebuilding is unlikely under the Amendment 13 proposed F levels for GOM cod, SNE/MA yellowtail flounder and SNE/MA winter flounder.

In summary, many factors may slow a recovery, but overfishing during rebuilding should not be one of them.

3.2 Species With a Skewed Age Distribution

In principle, if a stock experiences constant mortality and constant recruitment for a given SSB, it settles into the SAD where the number in each age class does not change with time. Stocks that have highly variable recruitment punctuated by very strong year classes will have an age distribution that is heavily skewed relative to the SAD. In Section 2.2 we showed that a rebuilt stock with a heavily skewed age distribution has a high chance of dropping below the biomass threshold even if harvest levels are at or below MSY. Here we use GB haddock, a stock that is not rebuilt but is on its way, and Pacific hake (whiting), a stock that was rebuilt but has since dropped below the management threshold, as examples of stocks with skewed age distributions. These two stocks are not unique, as many stocks exhibit highly variable recruitment. GB haddock and Pacific hake are just good examples, clearly illustrating our points from Section 2.2.

Georges Bank Haddock

The spawning stock of Georges Bank (GB) haddock has increased steadily since 1993, crossing the overfished threshold (1/2 SSB_{MSY}) in 2003, followed by a slight drop below the threshold in 2004 (Figures 28a and 28b; NEFSC 2005b). GB haddock recruitment is historically punctuated by anomalously strong recruitment events, and the stock SSB increases dramatically following these events (Figure 28). The steep recent increase in SSB is the result of the relatively strong 1997 and 1999 year classes, combined with low fishing mortality rates (below F_{MSY}). Although there is still much uncertainty in the strength of the 2003 year class (because they have not yet recruited to the fishery), the current estimate is the highest in the time series (Figures 28a and 28b; NEFSC 2005b). If this estimate is accurate, then the SSB of the stock will likely increase dramatically as the cohort grows and matures, possibly crossing the rebuilding target of SSB_{MSY} in a few years. However, if there are no additional strong recruitment events, once the 2003 cohort moves out of the population, the SSB will decline dramatically.

To show how skewed the 2004 age distribution is, we computed the SAD of GB haddock. We estimated the parameters α and β of the Beverton-Holt stock-recruitment model using estimates of SSB_t and R_{t+1} provided in the 2005 assessment (NEFSC 2005b). Next, we select initial abundance estimates for each of the age classes of haddock (nine age classes are used in the assessment; NEFSC 2005b). The initial values do not matter because the population will ultimately reach the SAD from any starting abundance, if given sufficient time. We use averaged estimates of weight at age (w_a) and maturity at age (f_a) from 2001 to 2004 to compute the SSB_t ($SSB_t = \sum_{a=1}^{x} w_a N_{t,a} f_a$), which we then use with stock-recruitment parameters to produce estimates of recruitment for the following year from the Beverton-Holt S-R curve and project the population until it settles into the SAD. In the example of a skewed age distribution in Section 2.2, we estimated the SAD in the absence of fishing (F = 0). However, since GB haddock will experience fishing, here we estimate the proportion of the population abundance ($\overline{p}_a$) in each age class in the SAD assuming both natural and fishing mortality (F = F_{MSY} = 0.26)

$$\overline{p}_a = \frac{N_{t,a}}{N_t} \tag{13}$$

In Figure 29a, we show the 2004 proportional abundance by age class of GB haddock and the proportional abundance if the population were in the SAD. It can be seen that the population is heavily skewed from the SAD: there are more age-1, 4 and 6 fish (resulting from the strong 1997, 1998 and 2003 year classes) and fewer age-2 and 3 fish (relative to the SAD). Figure 29b shows log-transformed abundance to allow for the differences in each age class to be clearly seen.

Although in Section 2.2 we showed that a population that is skewed towards the younger age classes has a greater chance of long-term recovery, we are not suggesting that a "rebuilt" stock skewed towards younger age classes is guaranteed long-term recovery. How a skewed age distribution affects a stock's long-term recovery depends on the stock in question, and should be examined on a case-by-case basis. In our example, we assumed no stochasticity in the stock-recruitment relationship to show the underlying relationship between a skewed age distribution and long-term recovery. In general, there is much variation in most stock-recruit relationships, and GB haddock is no exception. If the 2003 year class causes the GB haddock SSB to exceed SSB_{MSY}, and if management views this as a rebuilt stock and sets quotas at or near MSY, then the stock may quickly decline, depending on future levels of recruitment. However, we will show with our next example species that a "rebuilt" stock with a skewed age distribution does not have to experience high levels of harvest for there to be only short-term recovery.

Pacific Hake

Pacific hake provides an excellent example of what may happen to a stock that is considered rebuilt but has a skewed age distribution. The stock biomass of Pacific hake declined rapidly from 1980, dropping below the management threshold (analogous to B_{MSY}) of 40% B_0 (B_0 is the assumed virgin biomass) in 1995, and eventually below the minimum stock size threshold (MSST; analogous to 1/2 B_{MSY}) of 25% B_0 in 1999 (Figure 30). In 1999 there was a very strong recruitment event, and as this year class grew and matured, the stock biomass increased and surpassed the 40% target in 2003. The stock biomass has since declined, the result of the 1999 year class moving out of the population, and no further strong recruitment events (Figure 30; also see Helser et al. 2006).

It is important to note that the stock is declining in the absence of overfishing. In our past examples we showed that a recovered stock ($B \geq B_{MSY}$) may not be able to withstand the certain levels of removal below MSY from the stock if the age structure is sufficiently skewed in a particular direction. Annual quotas for Pacific hake have been well below the most recent estimate of MSY (573,945 mt), and landings have been below the quota since

2000. Thus, a rebuilt stock with a skewed age distribution does not need to experience large amounts of harvest to drop below the rebuilding, or even the overfished threshold.

3.3 Uncertainty

Uncertainty arises in many aspects of fishery management, from the assessments of stock status and future projections to target quotas and regulations aimed at achieving a particular F. Both process and observation uncertainty affect our understanding of stock status and our ability to predict how fast it can recover. Recall that observation uncertainty results from limited information about the system, and can be reduced by additional observations. Biased survey indices or limited or no information about discards can be classified as observation uncertainty. Process uncertainty, on the other hand, is due to random fluctuations of the system and is inherent in the system being observed. Wide fluctuations in recruitment such as those discussed above for GB haddock and Pacific hake are examples of process uncertainty.

Here we provide examples of how both observation and process uncertainty may impact our understanding of stock status and the accuracy of rebuilding projections. We use two stocks of yellowtail flounder that are in much worse condition than originally predicted (Figure 31). Although there may be multiple factors influencing our understanding of these stocks, for the case of GB yellowtail it appears that uncertainty in the stock's SSB in recent years (observation uncertainty) led to optimistic projections and rebuilding timelines. Alternatively, CC/GOM yellowtail is worse off than predicted in part due to poor recruitment events (process uncertainty) in recent years.

Georges Bank Yellowtail Flounder

The case of GB yellowtail flounder is a good example of how observation uncertainty can influence the perception of stock status. For GB yellowtail, observation uncertainty came in the form of retrospective bias in the virtual population analysis (VPA) estimates of stock biomass and exploitation rates. In a VPA, there is often much uncertainty in estimates of the most recent years, and stock assessments typically report the amount of uncertainty in the estimates, and direction of the bias (whether the biomass or fishing mortality rates are over- or underestimated; see Mohn (1999) for more on retrospective bias).

In the 2002 update assessment for GB yellowtail, the best estimate of SSB in 2001 was 39,000 mt and F was 0.19 (NEFSC 2002a). Given these estimates and reference points of SSB_{MSY} = 58,800 mt and F_{MSY} = 0.25, the stock was no longer overfished ($SSB_{2001} > 1/2\ SSB_{MSY}$) and was not experiencing overfishing ($F < F_{MSY}$). Projections using the 2001 estimates were made assuming a 15% reduction in F in 2002, then solving for the future F that resulted in 50% chance of crossing SSB_{MSY} by 2009 (F_{Rebuil}; Figure 32). An $F_{Rebuild}$ of 0.22 would allow for a 50% probability of rebuilding by 2009 (NEFSC 2002a). However, future assessments showed that there was strong retrospective bias in these estimates. The 2003 assessment estimated that in 2001 SSB was 16,000 mt, and F was 0.48, and the 2004 assessment estimated SSB in 2001 to be 9,000mt and F was 0.88. In 2005, a benchmark assessment was conducted and 2001 SSB was estimated at 9,900mt and F was 0.9 (NEFSC 2005b). With the reference points remaining the same throughout the assessments, the GB yellowtail went from not overfished and not experiencing overfishing (B-Ratio = 0.66; F-Ratio = 0.88) to overfished and experiencing overfishing (B-Ratio = 0.17; F-Ratio = 3.6) because of observation uncertainty. The current estimates of stock SSB in 2004 is 15,705mt (B-Ratio = 0.26; Figure 32) with F = 1.18 (F-Ratio = 4.7; Figure 33; NEFSC 2005b). The patterns of retrospective bias may still exist, and that the SSB in 2004 may be overestimated, and F may be underestimated. The exact source of the retrospective bias remains unknown, but it was estimated that landings being underestimated by 3,000 mt or natural mortality (M) being four times the rate used in the assessment would produce the observed bias.

Although uncertainty in M may not be the source of bias in the GB yellowtail assessment, incorrectly assuming M to be a certain value when it is not can greatly impact assessment results, rebuilding projections and management reference points. For most stock assessments, M is assumed to constant across age classes and is fixed around 0.2. In Figure 34 we show what uncertainty around a parameter such as M might look like. Although the mean of the distribution is 0.2, the probability that M is greater than 0.2 is 50%, and the probability that M is greater than 0.4 is approximately 14%. In this example, rather extreme values (>0.4) are still somewhat likely. If this probability distribution were to characterize our uncertainty for a particular stock, then assuming M = 0.2 could be very problematic. If M were greater than the value assumed, the results from stock assessment and projections will be too optimistic, with stock size and productibity overestimated and rebuilding time underestimated. The converse is true is M were less than the value assumed. Finally, it is likely that values of M are correlated in time from one year to the next, and this implies the need for caution in both assessment and prediction (Shea and Mangel 2001).

Cape Cod/Gulf of Maine Yellowtail flounder

The CC/GOM stock provides a good example of process uncertainty. Stochastic projections of CC/GOM yellowtail flounder SSB in the 2002 stock assessment predicted that the stock would cross SSB_{MSY} in 2009 if F were reduced from 0.75 in 2001 to 0.64 in 2002 and to 0.06 for the remainder of the rebuilding period (2003 – 2009; Cadrin and King 2002). However, the 2005 stock assessment indicates that the projection was too optimistic, with F higher (Figure 35) and SSB lower (Figure 36) than predicted (NEFSC 2005b).

Mean estimates of recruitment along with 95% confidence intervals used in the stock projection from 2002 to 2009 appear in Figure 37. However, the 2005 assessment indicates that the 2002 and 2003 recruitment events were the lowest in the time series, at approximately 3.7 and 4 million age-1 fish, respectively, (Figure 37; NEFSC 2005b) compared to the 10.5 million average from 1985 – 2001. In addition, the 2004 year class was below average, at approximately 6.2 million fish. Because of these poor year classes, the 2002 projections were far too optimistic, with the 2004 SSB at 25% of the projected estimate (B-Ratio = 0.09; Figure 31), and F is well above the level needed to rebuild (F-Ratio = 4.38; Figure 28). It should be noted that the $F_{Rebuild}$ shown in Figure 36 is not the target F for 2004. The rebuilding clock for CC/GOM yellowtail flounder was reset in 2004, and the rebuilding plan allows for overfishing (target F = 0.26) through 2008 (Swasey and Rosenberg 2006). As a result, F in 2004 is roughly three times the target level.

The examples of GB and CC/GOM yellowtail also highlight the danger of allowing overfishing during rebuilding. In the case of GB yellowtail, observation uncertainty in the assessment resulted in the predicted stock biomass being much higher than it actually was. For CC/GOM yellowtail, process uncertainty in the stock-recruit relationship led to projections that were too optimistic because assumed production was much higher than the actual production. In both cases, the stock biomass was below the assumed level, so quotas set to achieve a target F assuming the wrong biomass resulted in F being much higher than the target. Although these situations were likely unavoidable, setting much lower target F values (below F_{MSY}) may have resulted in the F in 2004 being much lower than the actual value.

4 Conclusions

We have identified three situations which may be of particular concern and warrant focused attention by those interested in the rebuilding of stocks to healthy levels: 1) stocks where overfishing is allowed during the rebuilding period even if stock abundance is increasing; 2) stocks in which the age distribution is far from the stable age distribution and 3) situations in which observation uncertainty is ignored.

Overfishing during rebuilding

We have expolained that if biomass is sufficiently low, a population experiencing overfishing may still increase, giving the illusion of good management practice. However, if the stock is to be rebuilt, fishing mortality rates will have to drop much below F_{MSY} at some point. There is thus potential for great dislocation of the fishery or political pressure not to reduce fishing mortality rates appropriately.

Furthermore, the details of how much a population can grow while being overfished and how much F must be reduced depend not just upon B_{MSY} and F_{MSY}, but upon the shape of the production curve. That is, it is important to consider the shape of the production curve (if it can be determined) when setting future catch levels, since the population size where a stock is most productive may influence the amount of fishing mortality that can be sustained.

Although allowing overfishing during the rebuilding period may result in population growth (as has been the case for summer flounder), allowing overfishing may also stagnate growth or even result in a decrease, and SA black sea bass, snowy grouper and SA golden tilefish illustrate this problem. In both cases, substantial decreases in quotas are needed to enable rebuilding. For summer flounder, an estimated 28% reduction may allow for rebuilding by

2008 (NEFSC 2005a). For SA black sea bass, snowy grouper, landings will be decreased by approximately 39, 76 and 70.5%, respectively, to end overfishing. In addition, if higher levels of overfishing than predicted occur during rebuilding (as was the case for GOM cod, SNE/MA yellowtail flounder and SNE/MA winter flounder), then rebuilding may take longer than projected if alterations are not made to the rebuilding plan.

Stocks that are Rebuilt but with a Skewed Age Distribution

For stocks undergoing rebuilding, a single strong year class can result in dramatic increases in stock biomass. If stock biomass crosses the rebuilding threshold, it may quickly drop below the threshold as the cohort ages and moves out the population. In fact, the case of Pacific hake shows how quickly a "recovered" stock can drop below the rebuilding target as the cohort matures, even in absence of high levels of harvest. On the other hand, GB haddock has not yet crossed the rebuilding threshold, but may in a few years if in fact the 2003 year class materializes (there is much uncertainty in the strength of this year class) and matures. Thus, any case of recovery should be viewed with caution, and sources of dramatic increases in stock size be thoroughly investigated to avoid overexploitation.

Uncertainty

The final situation of concern results from uncertainty in rebuilding projections. Stock projections typically include process uncertainty (stochasticity) in one or a few biological parameters while observation uncertainty is typically ignored. Both process and observation uncertainty may greatly impact our understanding of stock status and our ability to accurately predict future stock sizes. The case of CC/GOM yellowtail flounder shows that even a particular type of uncertainty that is accounted for can be problematic. Recent recruitment events were the lowest in 20+ years, and projections that used past estimates of recruitment were too optimistic. The case of GB yellowtail flounder highlights the impact that observation uncertainty may have on projections. Stock sizes were overestimated in recent assessments, and the stock is well below predictions. In both cases of yellowtail flounder, optimistic projections allowed for higher levels of harvest, which further slowed the progress of rebuilding.

One is thus well-advised to consider 'the probability of probability' or 'confidence intervals' around probability estimates in the context of recovery and rebuilding. The existing regulatory framework, which considers only process uncertainty, fails to incorporate the additional source of error posed by observation uncertainty. This limitation, combined with the tendency of agencies to promulgate regulations that embody the bare minimum probability of success permitted under law, may go a great distance toward explaining the current outcomes of federal rebuilding programs. However, the relevant statutes require the use of best available science - including the best mathematical science – and this requires recognition of all sources of uncertainty. To do otherwise improperly conceals the hidden policy decisions associated with the use of point estimates, and institutionalizes a high likelihood of failure to achieve rebuilding/recovery goals. The natural tool for decision-making under uncertainty is risk analysis (Anand 2002), which is well suited for dealing with probability intervals rather than point estimates. Such approaches must become central to recovery planning and rebuilding goals.

In summary, our work suggests the following guidelines:

1) For a greater chance of recovery within the rebuilding timeline, overfishing should not occur. In most cases, allowing overfishing does not prevent reductions in quotas, it just delays them. Also, overfishing during rebuilding does not leave much room for error. If the stock abundance used for projections is estimated too high, or if target quotas are exceeded, overfishing may result in

slowed stock growth, or even a decline. Such stagnant rebuilding will ultimately lead to a longer rebuilding timeline and more dramatic reductions in quotas.

2) When a stock crosses the rebuilding threshold, the age structure of the stock must be considered and quotas be set with caution. If a rebuilding "success" results from a single strong year class, once that cohort leaves the population, the stock biomass may quickly drop below the threshold if no additional strong cohorts are produced. Therefore management must proceed with caution and avoid overestimations of stock status, and relying too heavily on single recruitment events to rebuild a stock.

3) Whenever possible, both uncertainty about biological unknowns and stochasticity in recruitment and/or survival should be incorporated into additional parts of a projection such as future catches or the stock size used as the start year in a projection. Such an approach would broaden projection confidence intervals, showing the wide range of possible rebuilding timelines. Having projections that show how truly uncertain we are about a stock's rebuilding may force managers to err on the side of caution when setting rebuilding quotas. In addition, because of the great deal of uncertainty in projections, it may be wise to focus management on whether or not the stock is above the rebuilding target at the current time, rather than on long-term time horizons.

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Table

Table 1. Target and actual F_{Ratios} and final F_{Ratio} (also called $F_{Rebuild}$) as well as target TAC and actual catch (landings + discards) for GB cod, GOM cod, SNE/MA yellowtail flounder, SNE/MA winter flounder and white hake. Target values and the final F_{Ratio} are from NEFMC (2003), while actual values are from NEFSC 2005b.

Stock	Target 2004 F_{Ratio}	Actual 2004 F_{Ratio}	Final F_{Ratio} (start year)	Target 2004 TAC (mt)	Actual 2004 Catch (including discards)
GB Cod	1.17	1.33	1 (2009)	3,949	4,583
GOM Cod	1	2.74	0.91 (2009)	4,850	5,898
SNE/MA Yellowtail Flounder	1.42	3.81	0.65 (2009)	707	300
SNE/MA Winter Flounder	1	1.19	0.72 (2009)	2,860	1,699
White Hake	1.87	2.14	0.36 (2009)	3,839	3,717

Figures

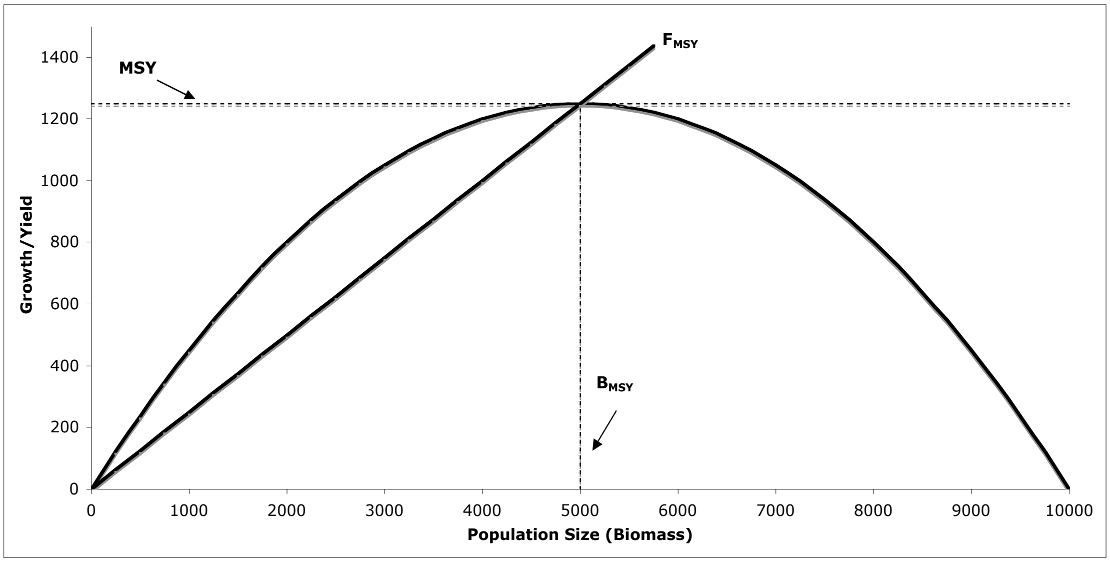

Figure 1. Renewable resource management is based on the notion of density dependence: that the growth rate of the population is zero when its size is zero, then increases until and peaks at some intermediate size, after which growth rate declines. These concepts are illustrated here in terms of a biomass or production model in which the measure of population size is total biomass (more complicated cases are considered later). They allow us to determine MSY, the population size or biomass that provides MSY, B_{MSY}, and the rate of exploitation at which MSY is achieved, F_{MSY}, assuming that harvest is approximately proportional (explained in the text) to biomass; i.e that Yield = FB where F is fishing mortality rate. The curve shown here is for logistic growth, described in the text with r=0.5 and K=10000.

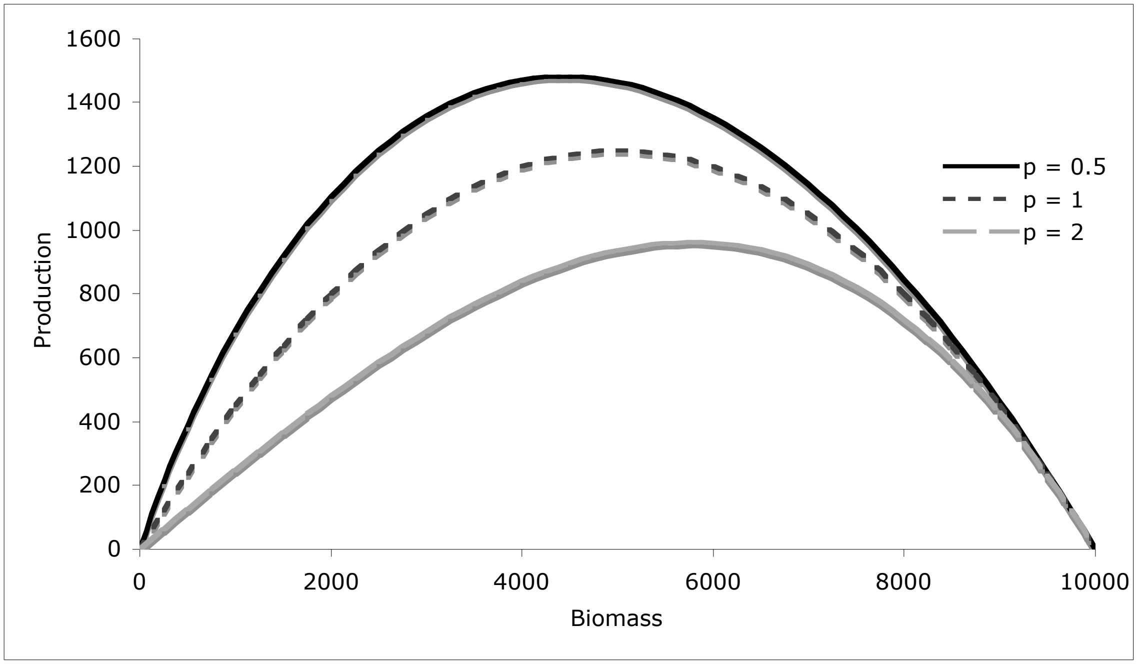

Figure 2a. The production function G(B) as a function of biomass for three different values of p, with the same value of maximum per capita productivity r.

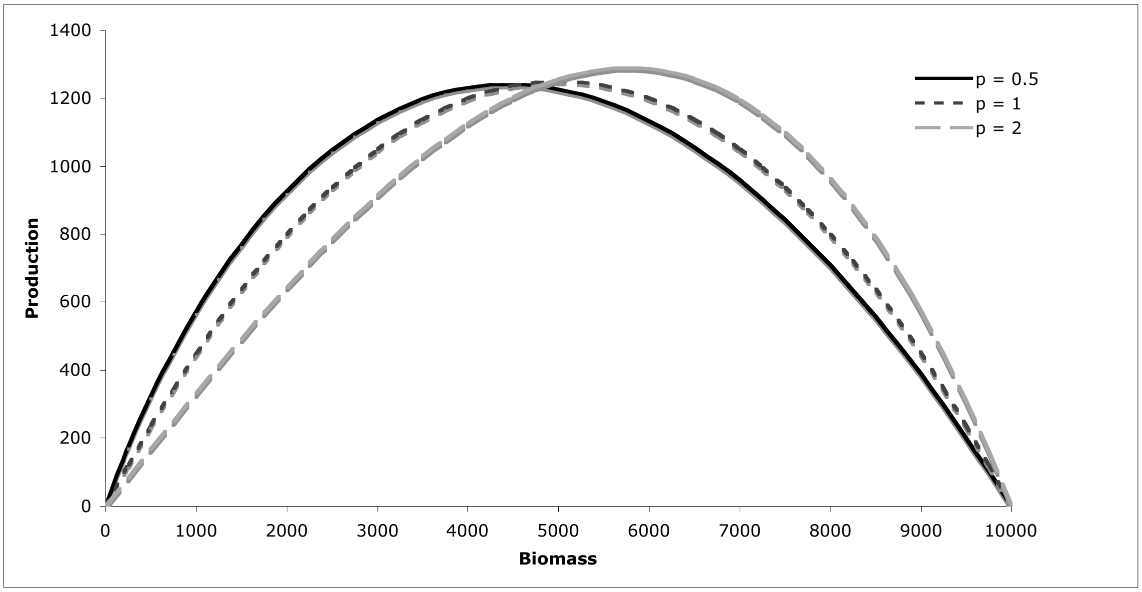

Figure 2b. By using Eqn 3, we are able to normalize maximum productivity for production functions in which the location of B_{MSY} varies. Here we have varied r to make total production approximately equal for 3 levels of p (r = 0.422 for p = 0.5; 0.5 for p = 1; and 0.649 for p = 2).

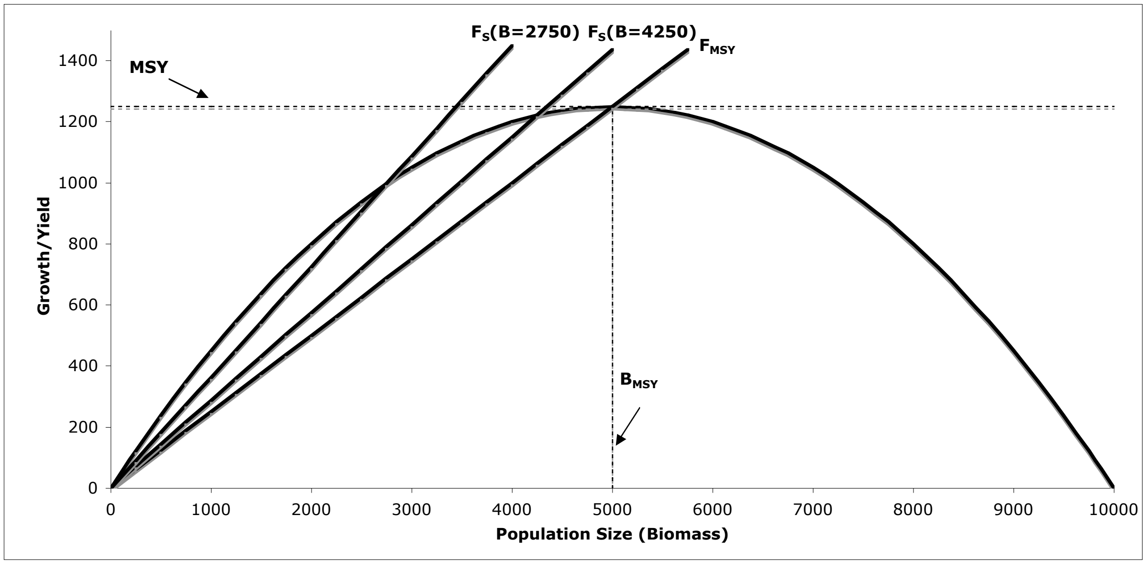

Figure 3a. Relationship between population size and growth (or yield), with management reference points B_{MSY} and MSY for the Schaefer model with r = 0.5, K = 10000. Sustainable fishing mortality rates are shown for the population at B_{MSY}, $F = F_{MSY}$; B = 4250, $F = F_S(4250)$ and B = 2750, $F = F_S(2750)$. Note that if the population is overfished ($B < B_{MSY}$) then the fishing mortality rate may exceed F_{MSY} and be sustainable. As long as production (the curve) exceeds removal (the line), the population will grow in time. However, the population will reach a steady state, determined by the intersection of the line and the curve that is below B_{MSY}.

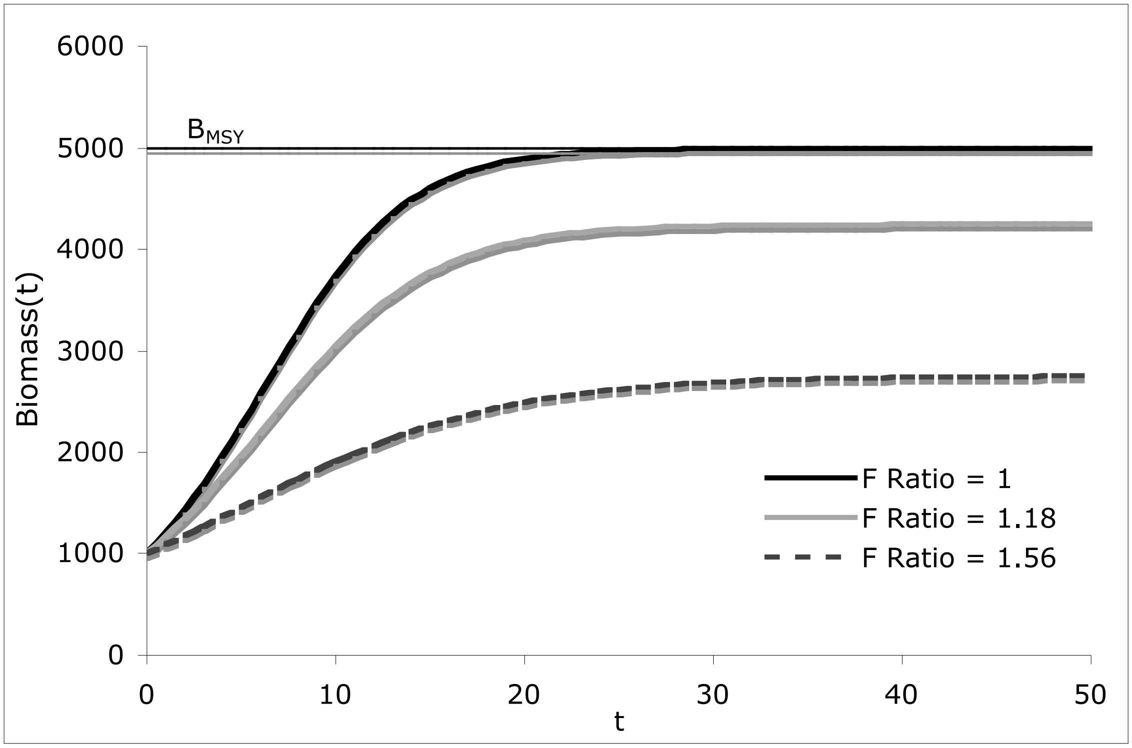

Figure 3b. Population trajectories for a depleted stock (B_0 = 0.1•K) under the different levels of F shown in Figure 3a. When overfishing occurs on a stock below B_{MSY}, the stock will asymptote below B_{MSY}. How far below it asymptotes depends on the level of overfishing.

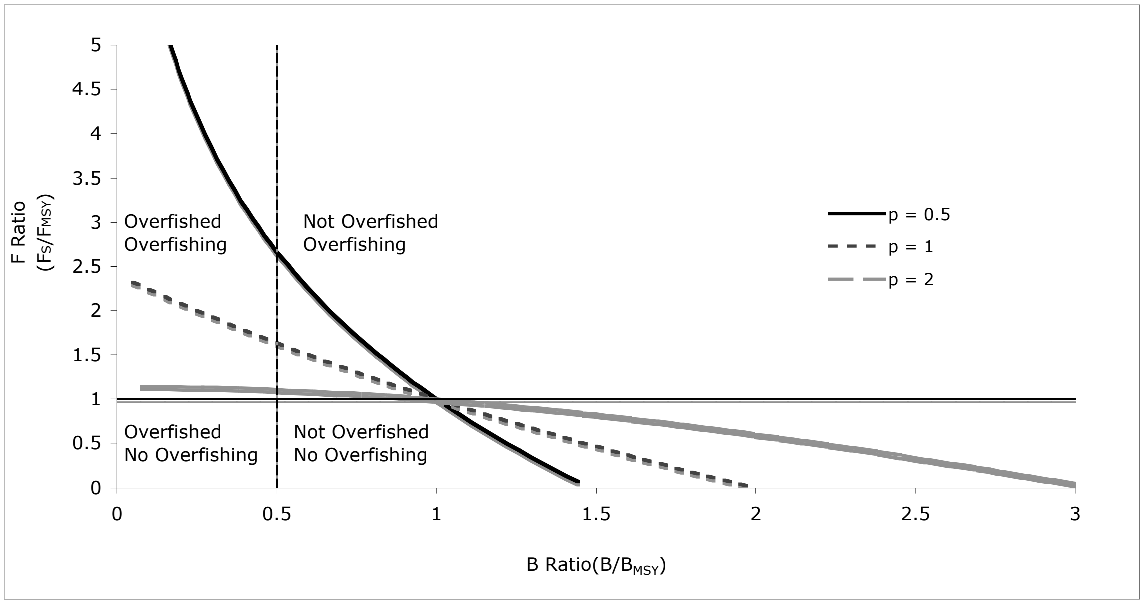

Figure 4. By plotting the F-Ratio against the B-Ratio we can determine when a population will increase even though it is overfished (an F-Ratio below the curve for a particular B-Ratio) and we characterize stocks according to their overfished and overfishing status.

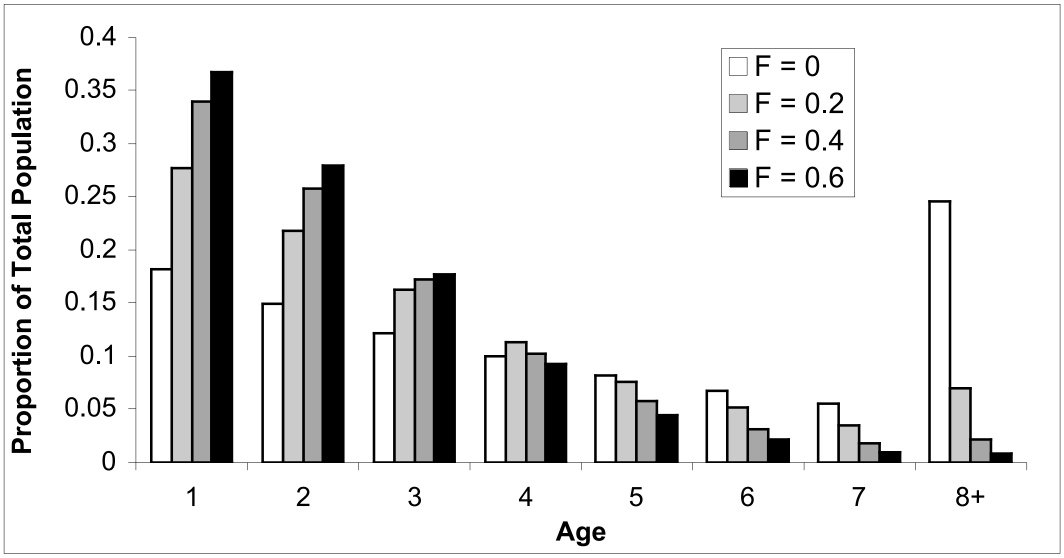

Figure 5a. An example of a stable age distribution under different intensities of fishing pressure, with constant selectivity (50% selectivity at age 2). Note that as fishing mortality rate F increases the fraction of individuals at older age continues to decrease; the bump at age 8+ is due to combining all of ages older than 8.

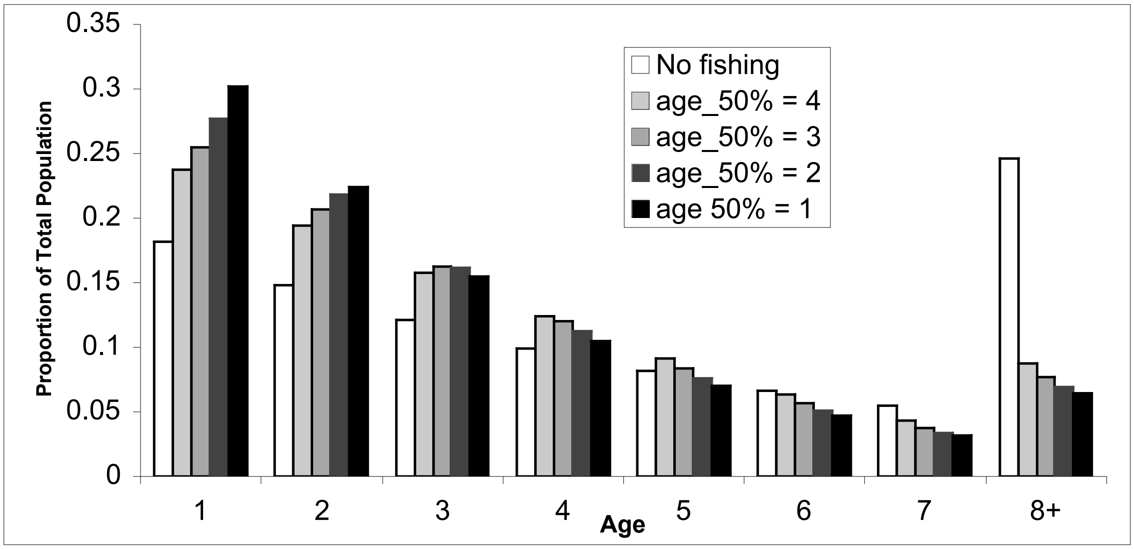

Figure 5b. Another example of the stable age distribution, showing the effect of changing the age at which fish are recruited to the fishery, by varying the age at which there is a 50% chance that a fish will be taken by the fishery (with F = 0.2).

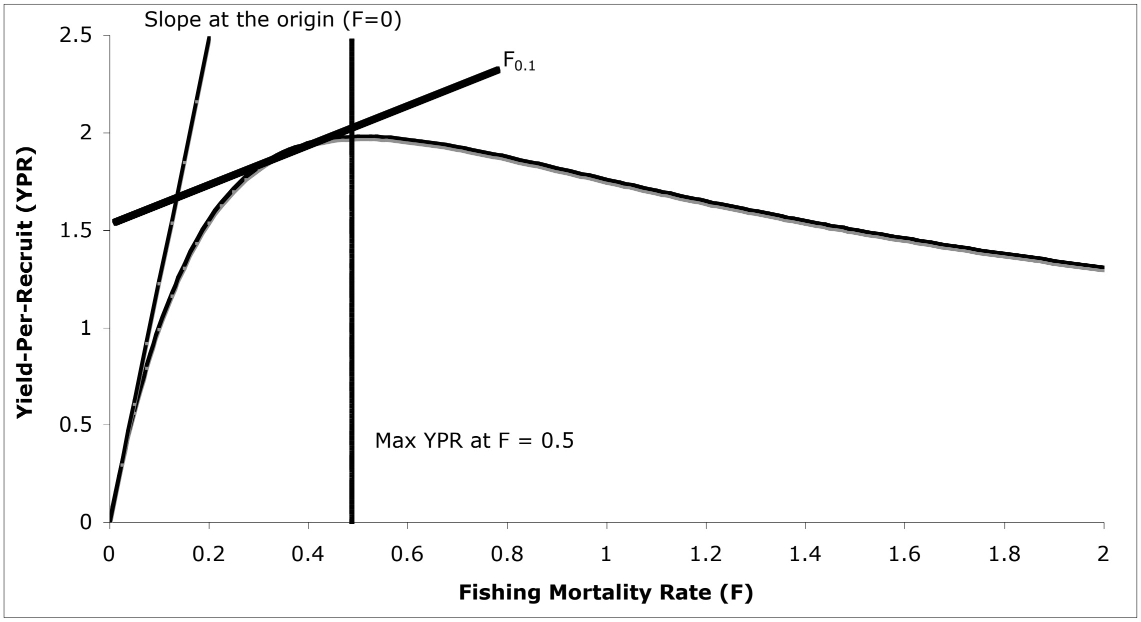

Figure 6. Yield Per Recruit is a peaked function of fishing mortality rate. The slope of this relationship at the origin (F=0) and at 10% of the relationship at the origin ($F_{0.1}$ line) are plotted to show how an $F_{0.X}$ is estimated.

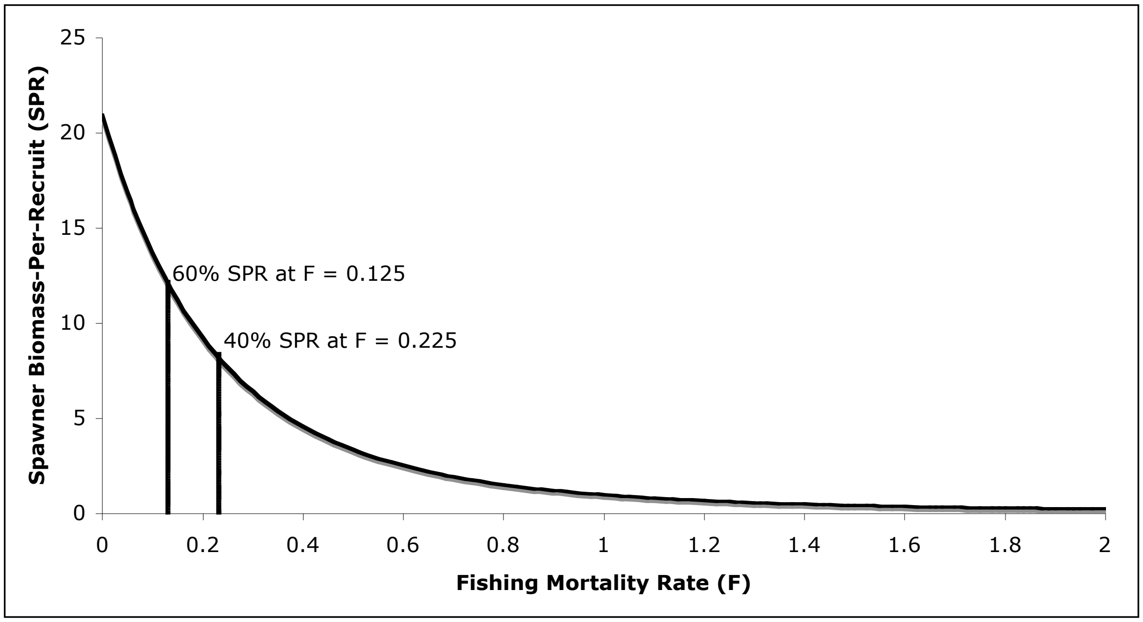

Figure 7. Spawning biomass per recruit is always a declining function of exploitation rate, because increasing levels of exploitation always mean that fewer fish are available for reproduction. Dotted lines represent potential fishing mortality rates set by management at 40% and 60% SPR.

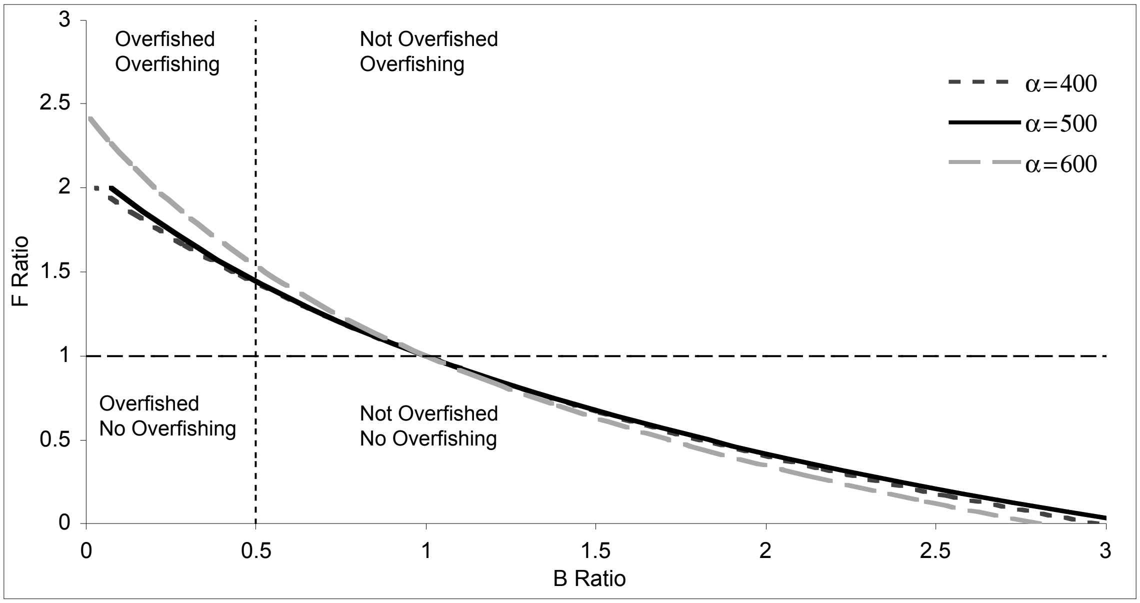

Figure 8. The F-Ratio/B-Ratio plot can be constructed for an age structured model. As before, the plot summarizes the status of the stock with respect to size and intensity of fishing pressure.

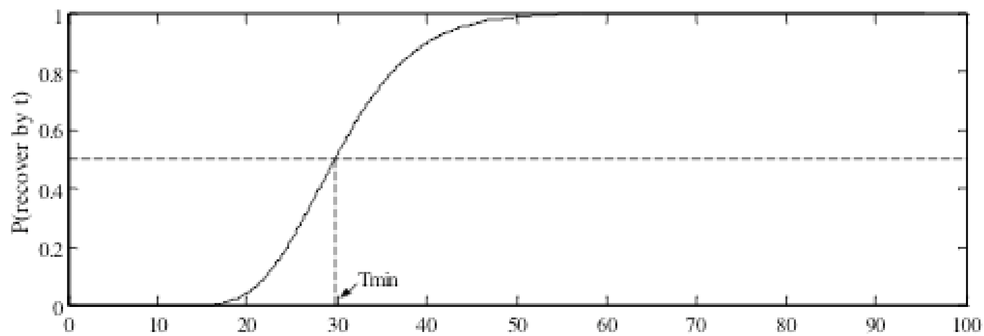

Figure 9. The probability of reaching a rebuilding goal (X = 5) by time t based on the best estimate of the deterministic component of population dynamics and the intensity of fluctuations. The parameters are r = 0.1, D = 0.005 and X(0) = 1; r was estimated from 10 observations of the process over a 20 year period so that P(r|data) = N(0.08,0.0007). Based on the intersection of the curve with the horizontal line at 50% probability of recovery, we conclude that the minimum rebuilding time is T_{min} = 30 years.

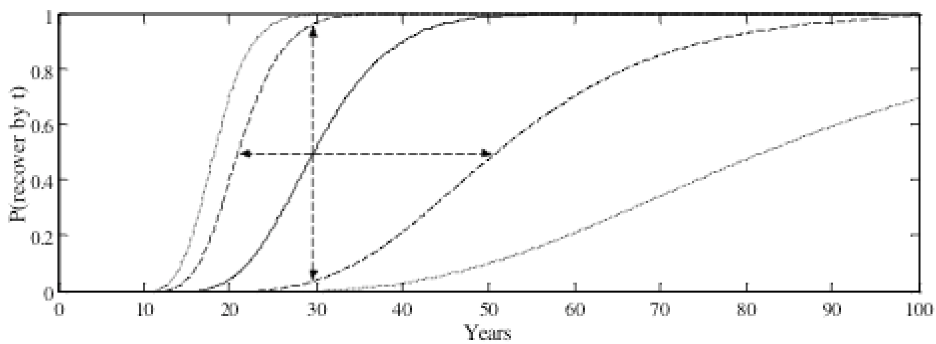

Figure 10. Recognizing observation uncertainty in r (Eqn 9) leads to the conclusion that there is not a single curve characterizing recovery, but a family of curves, each indexed by the fixed but unknown component of the biological dynamics. We have summarized those families of curves by showing the boundaries that include 80% (dashed) and 95% (dotted) of the trajectories.

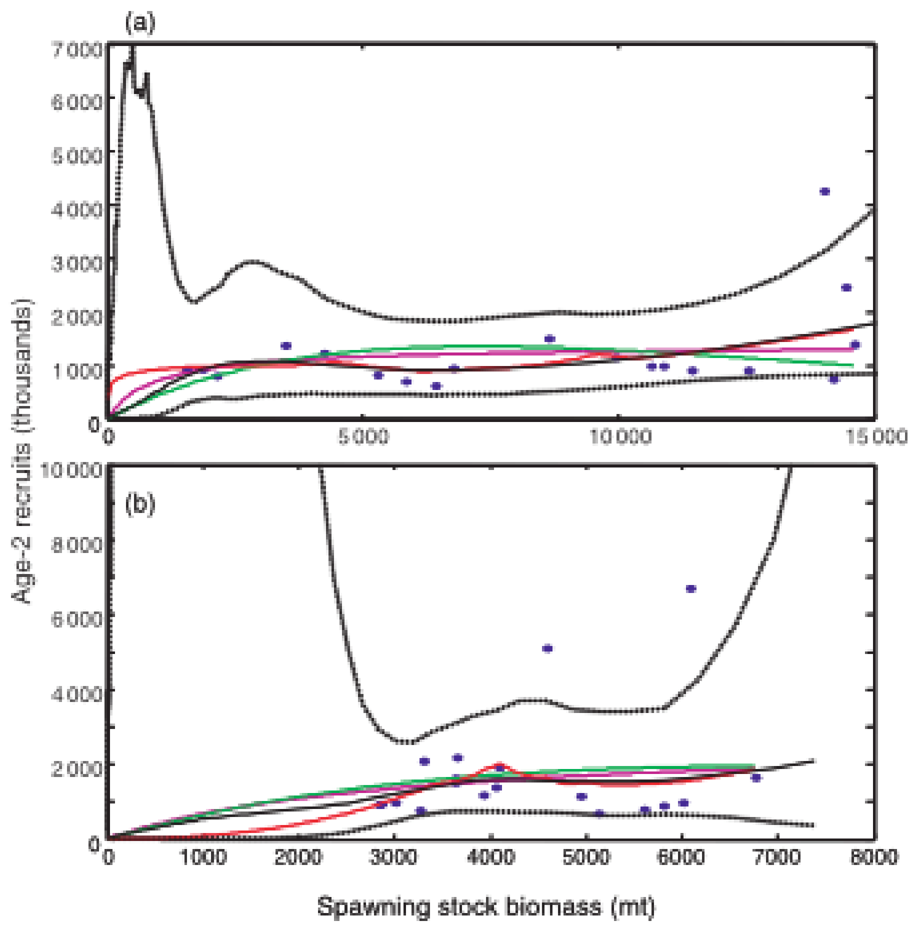

Figure 11. The implications of uncertainty in the stock recruitment relationship may be profound. Here we give an example, from Munch et al. (2005) concerning lingcod (*Ophiodon elongates*). The stock-recruitment relationships for northern (A) and southern (B) populations are shown. Points are observed data. The solid black line gives the posterior mean and the dotted denote 95% uncertainty bands of the Bayesian nonparametric method of Munch et al. The magenta line shows the best-fit Beverton-Holt model. The other lines are different parametric versions of stock recruitment relationships.

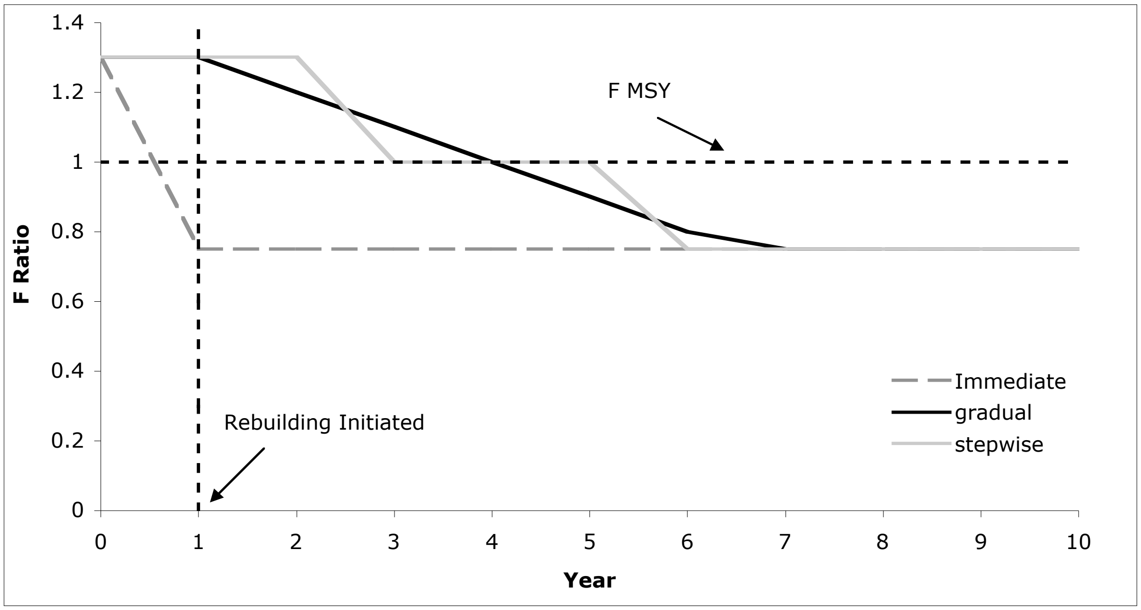

Figure 12. Three ways in which fishing mortality may be reduced to allow rebuilding. In year 0, it is determined that overfishing is occurring, with the F-Ratio = 1.3. For the stock to successfully rebuild, the F-Ratio must be lower than F_{MSY}, and this can be done instantly (from year 0 to year 1), in a stepwise manner (shown here dropping from F-Ratio =1.3 to 1.0, to 0.8) or gradually and continuously.

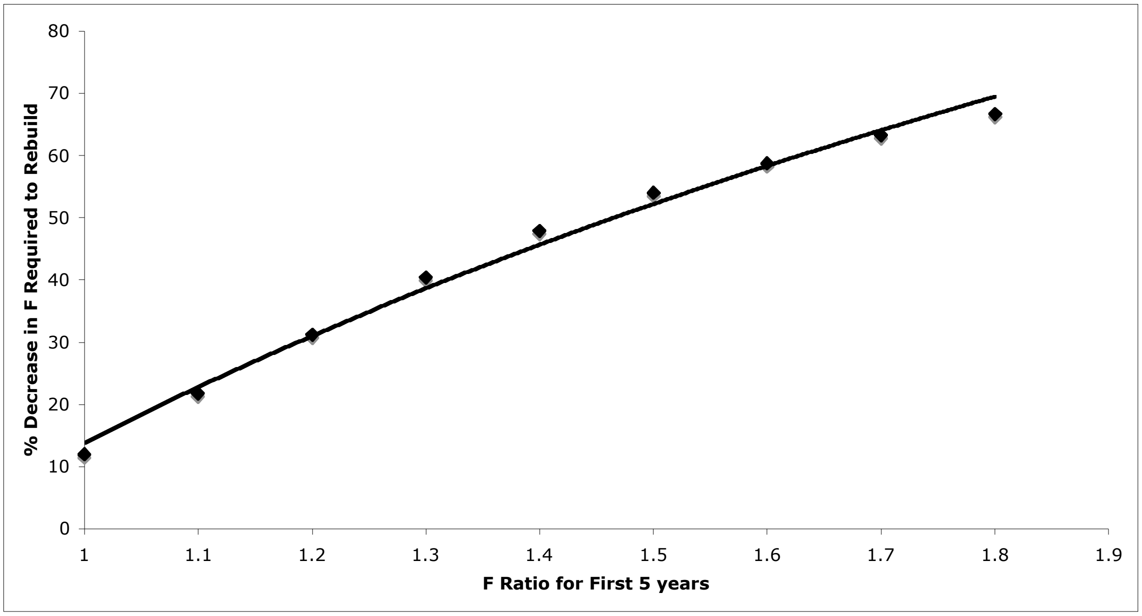

Figure 13. The relationship between the F-Ratio for the first 5 years of rebuilding and the F-Ratio for the final 5 years that will enable the population to recover within 10 years for a production model with B_0 = 2500, r = 0.5, K = 10000, p =1 . The line represents the best fitting logarithmic model (y = 94.739 log(x) + 13.781).

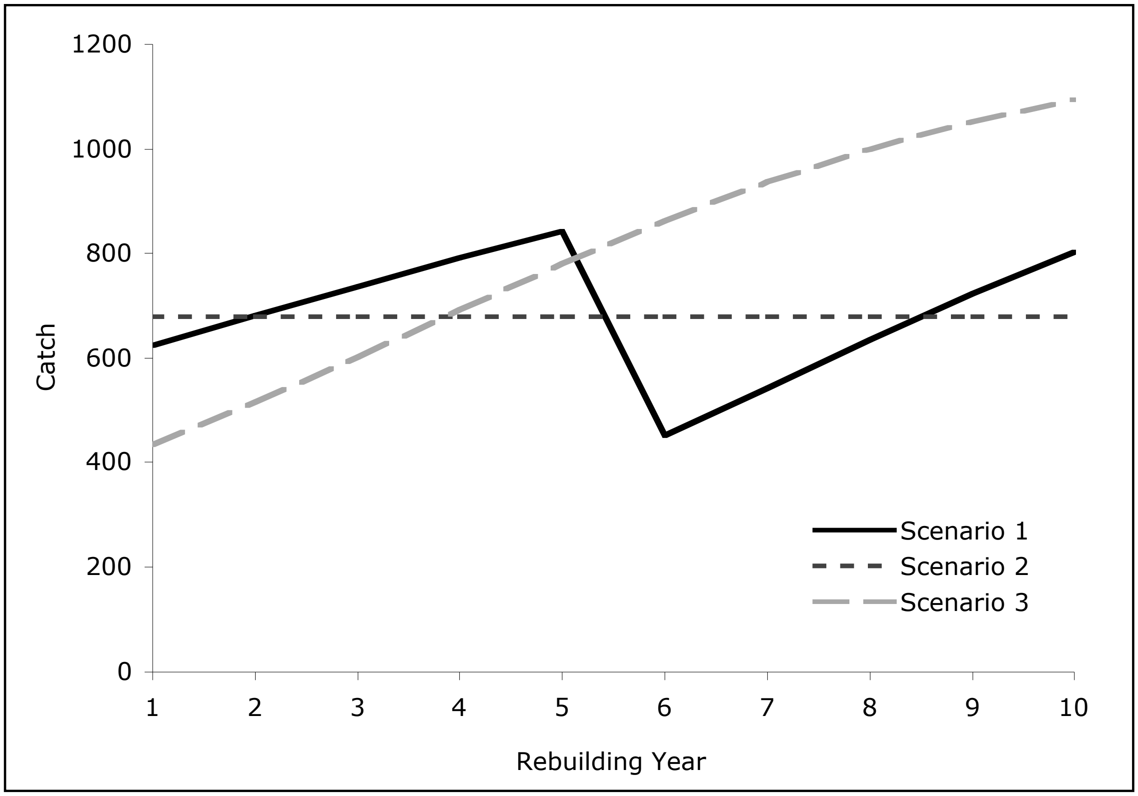

Figure 14. Impact of three scenarios on annual catch during a 10 year rebuilding period. Scenario 1 is a single reduction in fishing mortality rate (initial F Ratio = 1.3, reduced to 0.6 after 5 years), scenario 2 is a gradual reduction in F to allow for a constant catch, and scenario 3 in a constant F that allows for gradual increases in catch as the stock grows. In all cases, the stock is more likely to rebuild than not, but scenario 1 requires a serious dislocation to the fishery in year 5, or the stock will not be rebuilt, and scenario 3 results in a higher total catch over the rebuilding period (7900 compared to ~6800 for scenarios 1 and 2).

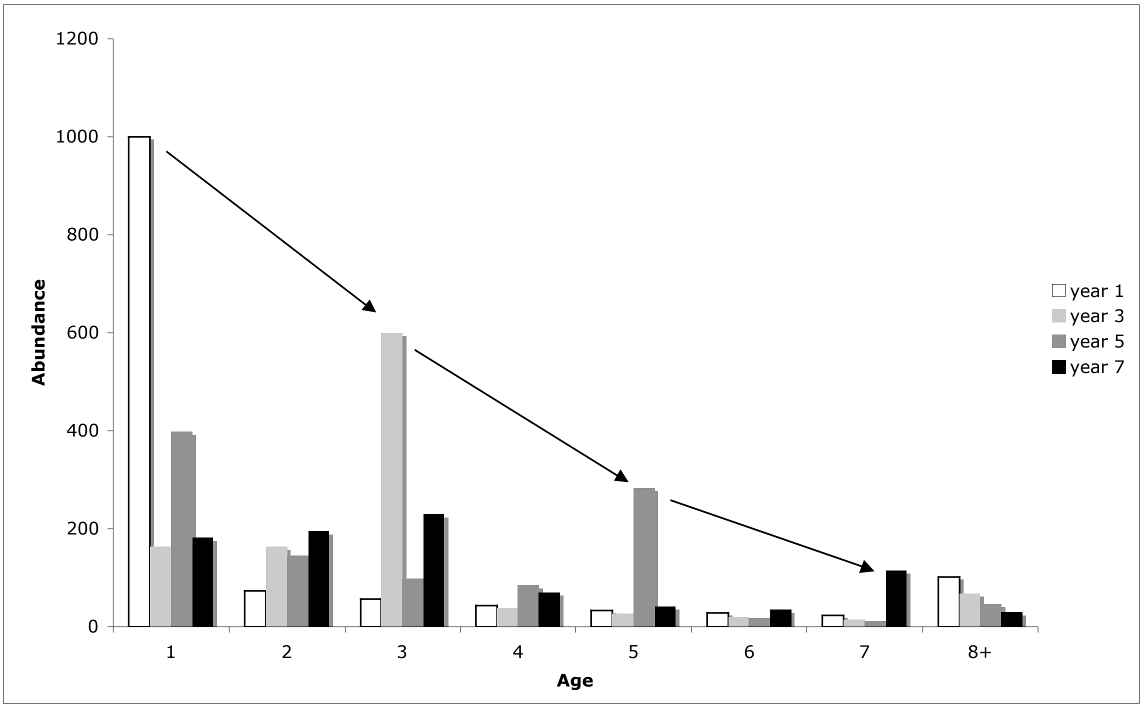

Figure 15. Illustration of a strong recruitment event moving through a population over time.. There is an extremely strong recruitment event in year 1 (dark blue bars), and this year class moves through the population, comprising the bulk of the population (years 3, 5 and 7) until reaching the maximum age, and disappearing from the population. When there are no subsequent large recruitment events, it is possible to conclude that the population has rebuilt, when it is in fact inappropriate to increase fishing mortality rates

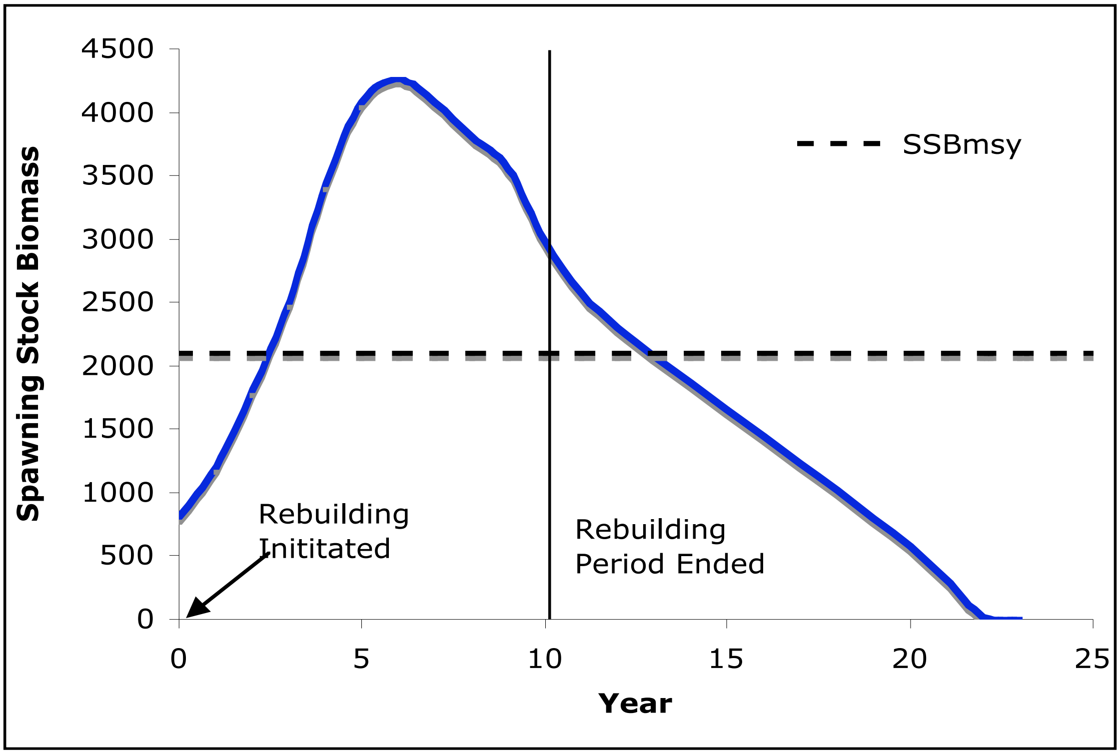

Figure 16. Projected SSB for a population that has an initial strong recruitment event followed by average recruitment (predicted by the B-H model). Once SSB > SSB_{MSY}, annual yield is set to MSY.

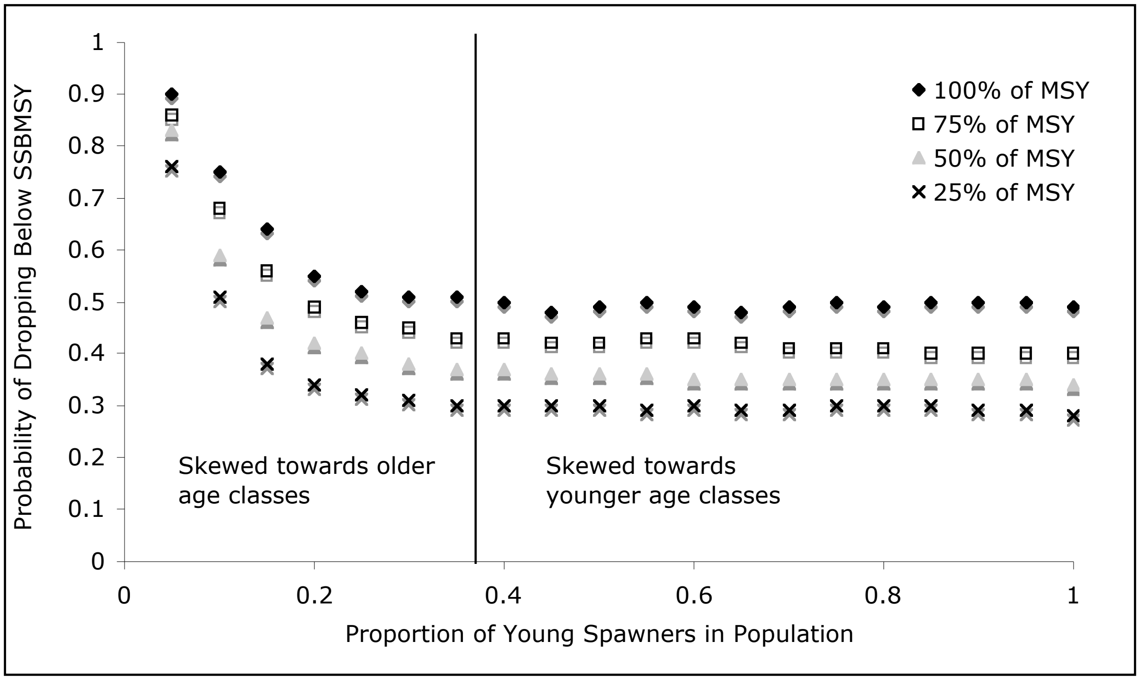

Figure 17. The proportion of young spawners in the population is another measure of skew in the age-distribution of a population. A population skewed towards older age classes has a high probability of dropping below SSB_{MSY} over the long-term under different levels of harvest (≤ MSY), whereas a population skewed towards younger age classes has a lower probability of dropping below SSB_{MSY}. The line at 0.37 represents the proportion of young spawners in the stable age-distribution. However, a population's SSB can be comprised of 37% young spawners and be far from the stable age distribution, thus highlighting the need for multiple measures to determine the skew of a population's age-distribution.

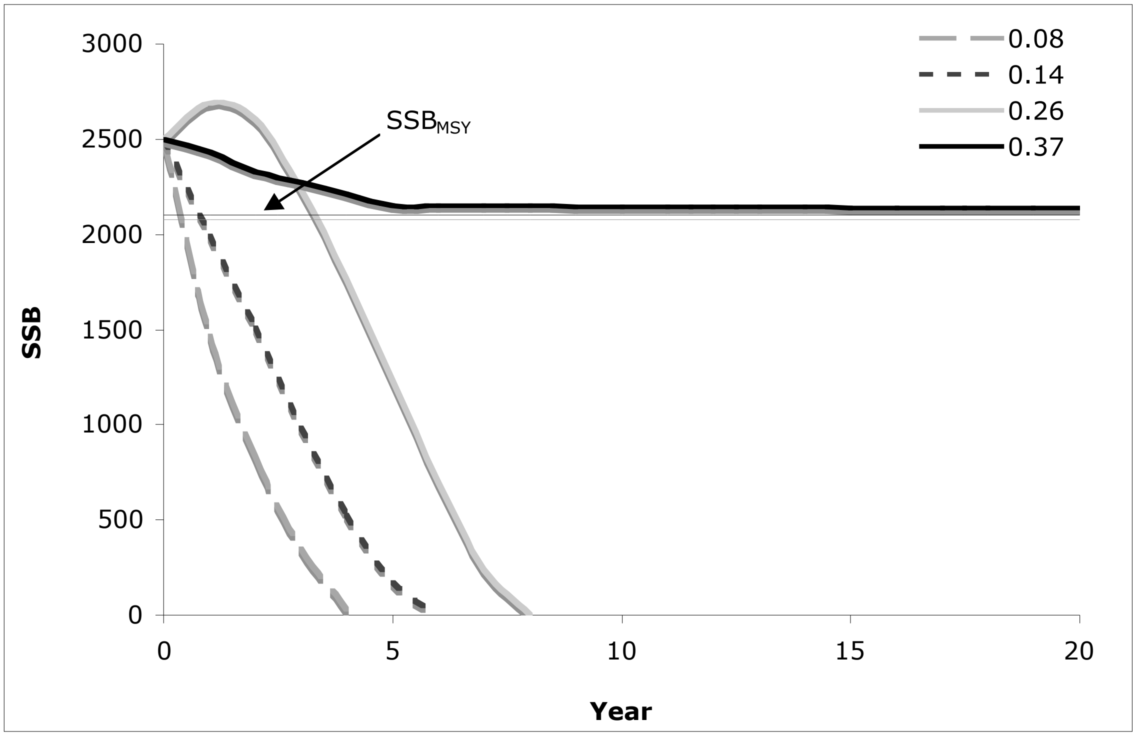

Figure 18. Specific trajectories of the population SSB for proportions of young spawners in the population at the time of recovery. If the population is at the stable age distribution (proportion of young spawners = 0.37, black line), MSY can be removed and the SSB will remain above SSB_{MSY}. If the population is skewed towards older age-classes (proportion of young spawners < 0.37), then removing MSY will cause the SSB to drop below SSB_{MSY}.

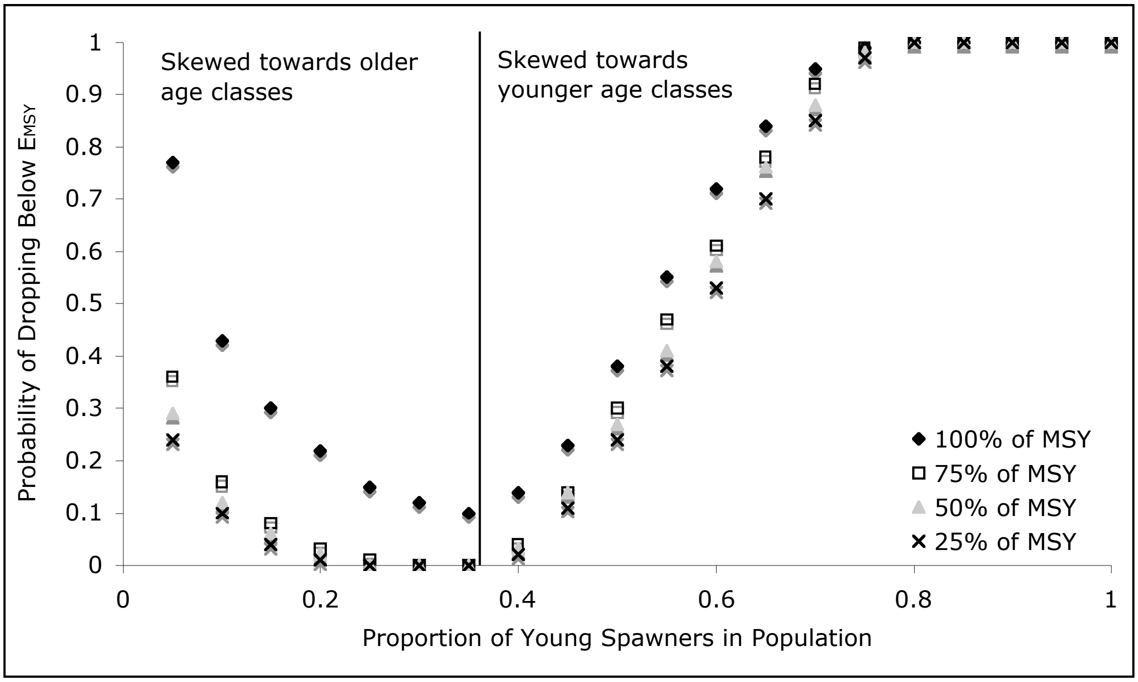

Figure 19. When the reproductive success of the population depends on egg production and egg quality, and not SSB, a population that is heavily skewed towards both older and younger age classes has a high probability of dropping below E_{MSY} (total egg production that produces MSY) over the long-term under different levels of harvest ($\leq$ MSY) whereas a population less skewed towards younger or older age classes has a lower probability of dropping below E_{MSY}. The line at 0.37 represents the proportion of young spawners in the population in the stable age distribution. However, a population's SSB can be comprised of 37% young spawners and be far from the stable age distribution.

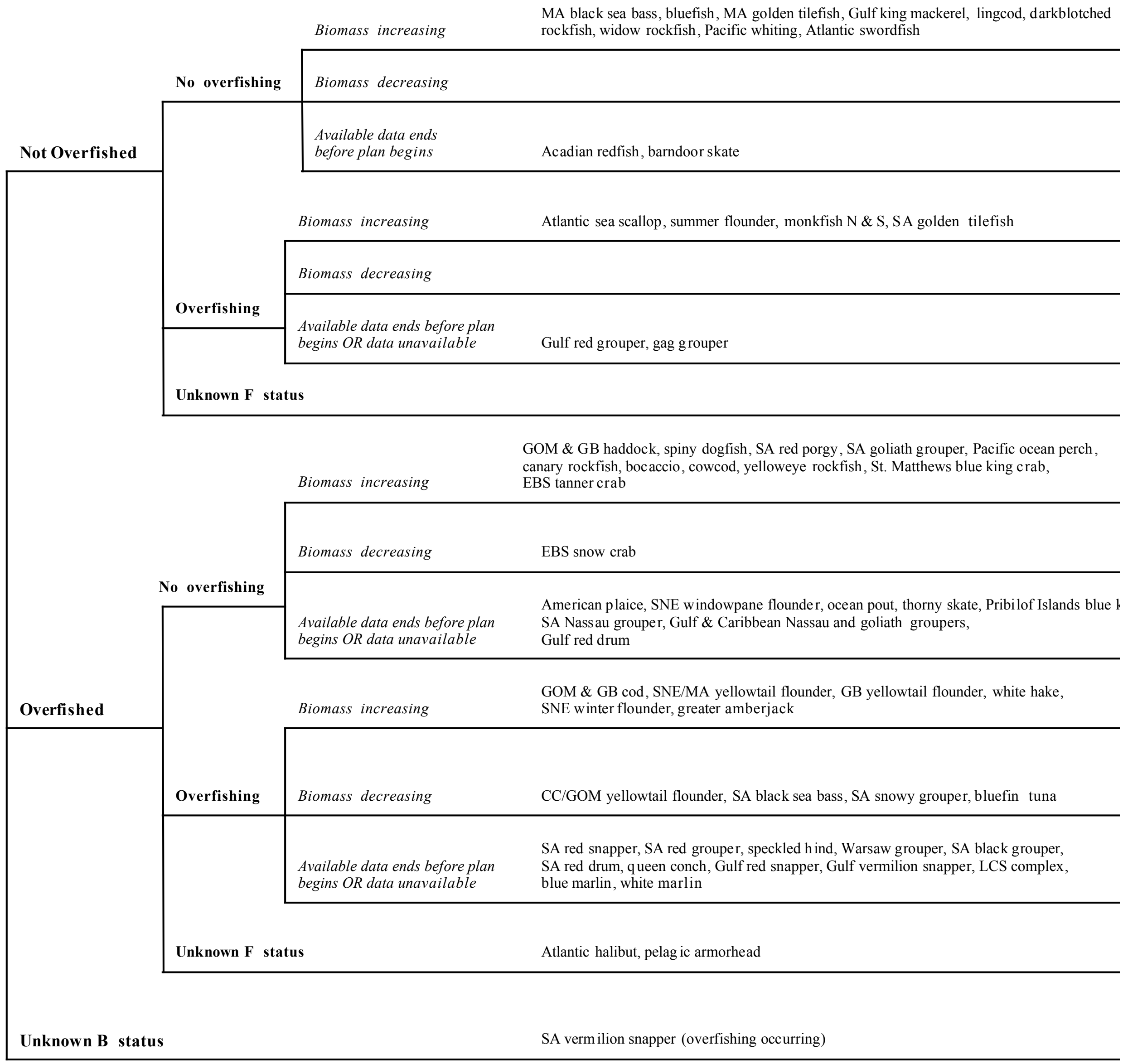

Figure 20. A classification tree categorizing the status of all stocks undergoing rebuilding in U.S. waters. The first branch of the tree indicates the stock biomass (overfished, not overfished or unknown). The second branch indicates current harvest rates (overfishing, no overfishing, or unknown). The final branch indicates biomass trend in the most recent years (increasing, stable/fluctuating, decreasing or unknown). Biomass trend is determined by fitting a linear regression to the biomass data from the implementation of the rebuilding plan.

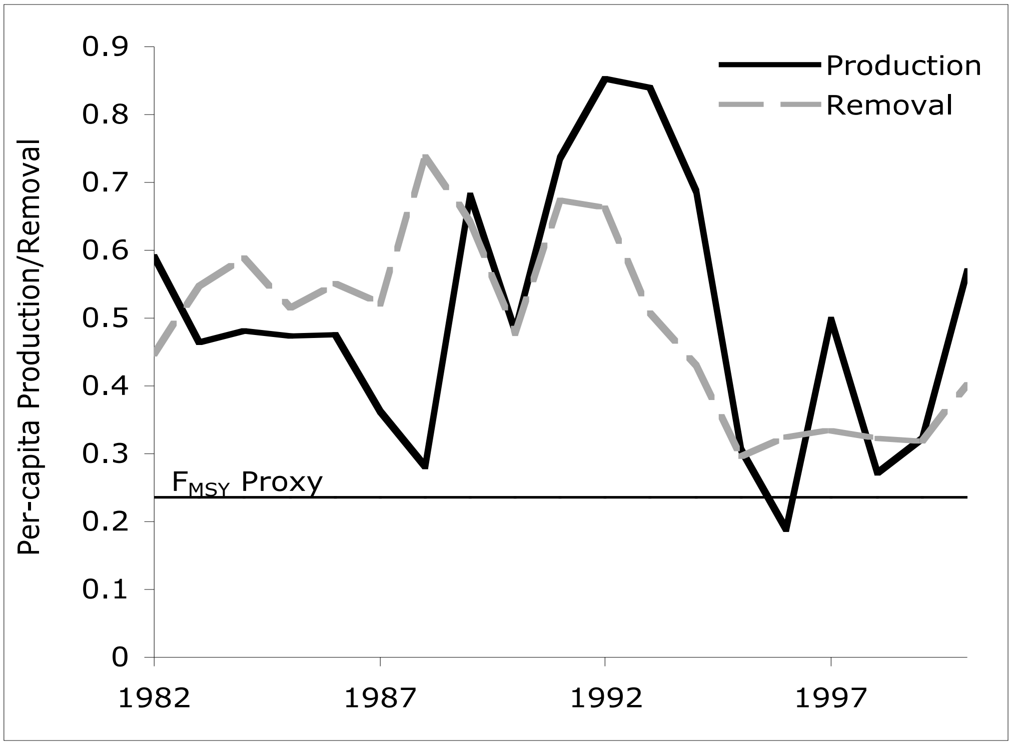

Figure 21. Summer Flounder per-capita production ($G(B_t)/B_t$; black line) and removal (C_t/B_t; dashed grey line) from 1982 to 2001. Population growth occurred in years when the black line exceeded the red line. The F_{MSY} proxy is calculated by converting the estimate of F_{MSY} (0.276) provided in NEFSC (2005a) into the per-capita removal, using 1-exp(-F_{MSY}).

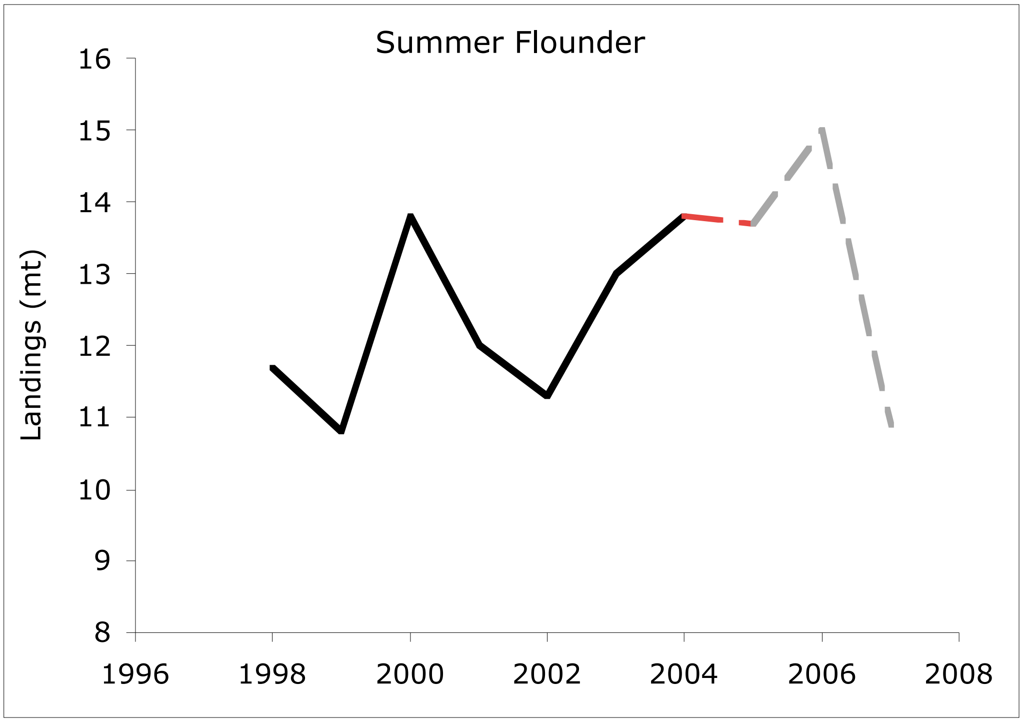

Figure 22. Landings of summer flounder in metric tons (mt). The black line represents the landings that have occurred and the dashed grey line represents the projected landings required to rebuild the stock by 2008 (NEFSC 2005a). The decrease projected from 2006 to 2007 is 28%.

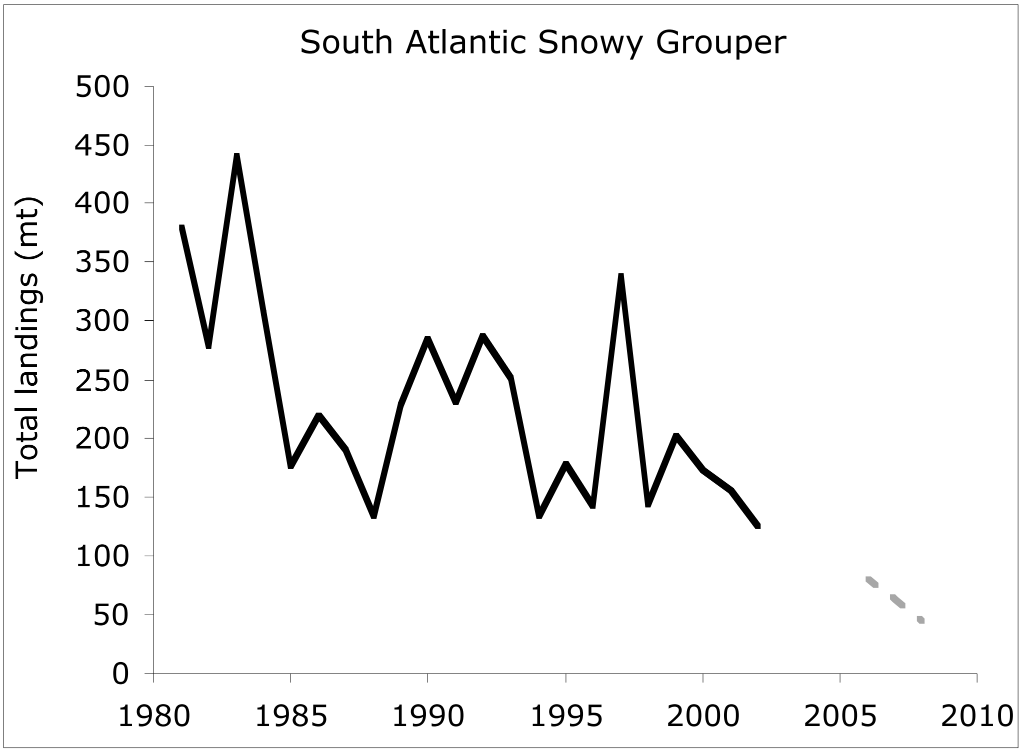

Figure 23. Total landings of snowy grouper in the South Atlantic from 1981 to 2002 (black line). The dashed grey line represents the Amendment 13C specified reduction in landings (SAFMC 2005). This is approximately a 76% reduction in landings over a three-year period.

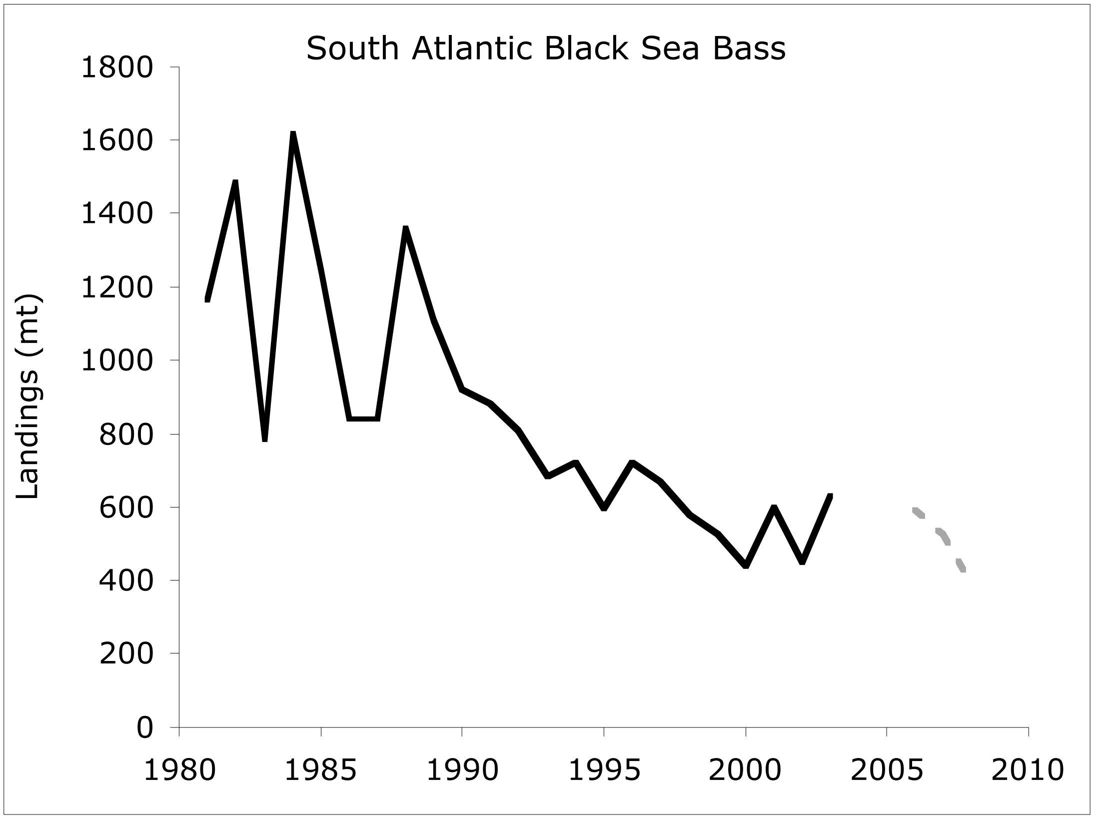

Figure 24. Total landings of SA black sea bass from 1981 to 2003 (black line). The dashed gray line represents the Amendment 13C specified reduction in landings (SAFMC 2005). This is approximately a 48% reduction in landings over a three-year period.

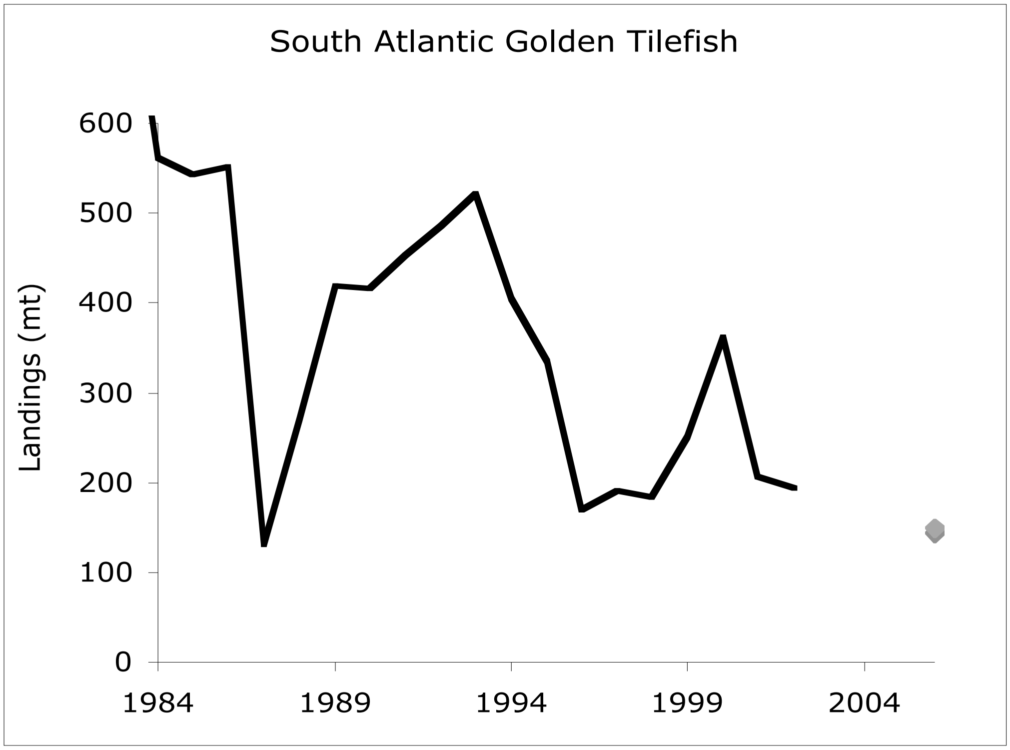

Figure 25. Total landings of SA golden tilefish from 1984 to 2002 (black line). The gray point represents the Amendment 13C specified reduction in landings (SAFMC 2005). This is a 22.6 % reduction in the 2002 landings, but a 70.5% reduction in commercial quota.

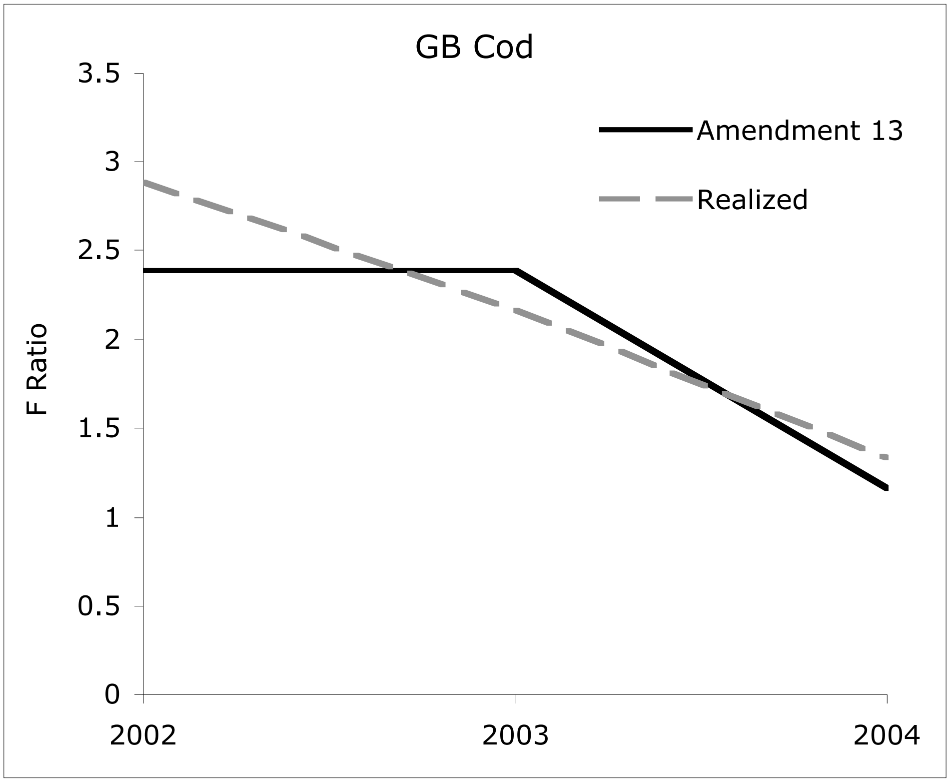

Figure 26a. Amendment 13 specified F_{Ratio} (black line; NEFMC 2003) compared to the most recent estimates of F_{Ratios} (dashed gray line; NEFSC 2005b) from 2002 to 2004 for GB cod. The 2002 and 2003 F_{Ratio} values from Amendment 13 were "assumed" in stock projections, where the 2004 F_{Ratio} is the target level for that year (NEFMC 2003).

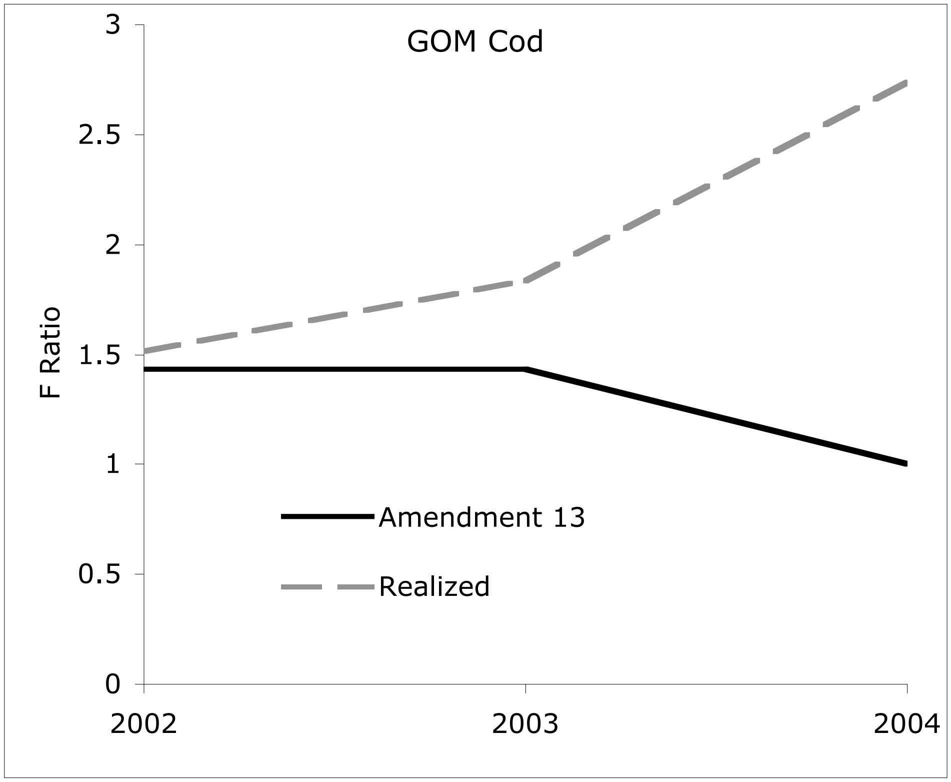

Figure 26b. Amendment 13 specified F_{Ratio} (black line; NEFMC 2003) compared to the most recent estimates of F_{Ratios} (dashed gray line; NEFSC 2005b) from 2002 to 2004 for GOM cod. The 2002 and 2003 F_{Ratio} values from Amendment 13 were "assumed" in stock projections, where the 2004 F_{Ratio} is the target level for that year (NEFMC 2003).

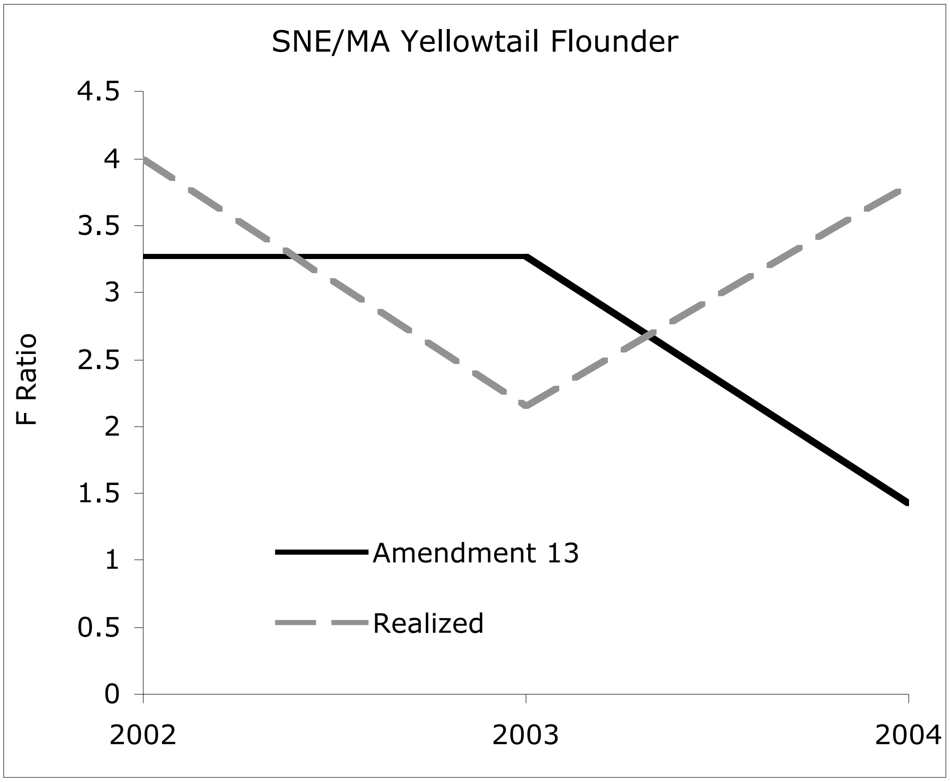

Figure 26c. Amendment 13 specified F_{Ratio} (black line; NEFMC 2003) compared to the most recent estimates of F_{Ratios} (dashed gray line; NEFSC 2005b) from 2002 to 2004 for SNE/MA yellowtail flounder. The 2002 and 2003 F_{Ratio} values from Amendment 13 were "assumed" in stock projections, where the 2004 F_{Ratio} is the target level for that year (NEFMC 2003).

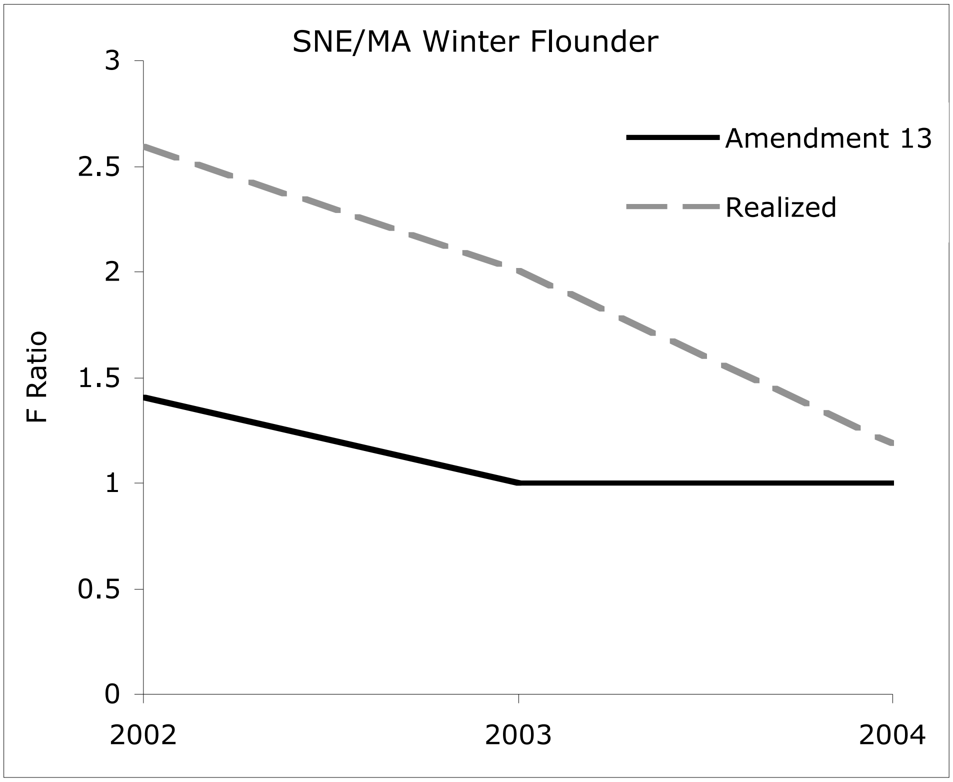

Figure 26d. Amendment 13 specified F_{Ratio} (black line; NEFMC 2003) compared to the most recent estimates of F_{Ratios} (dashed gray line; NEFSC 2005b) from 2002 to 2004 for SNE/MA winter flounder. The 2002 and 2003 F_{Ratio} values from Amendment 13 were "assumed" in stock projections, where the 2004 F_{Ratio} is the target level for that year (NEFMC 2003).

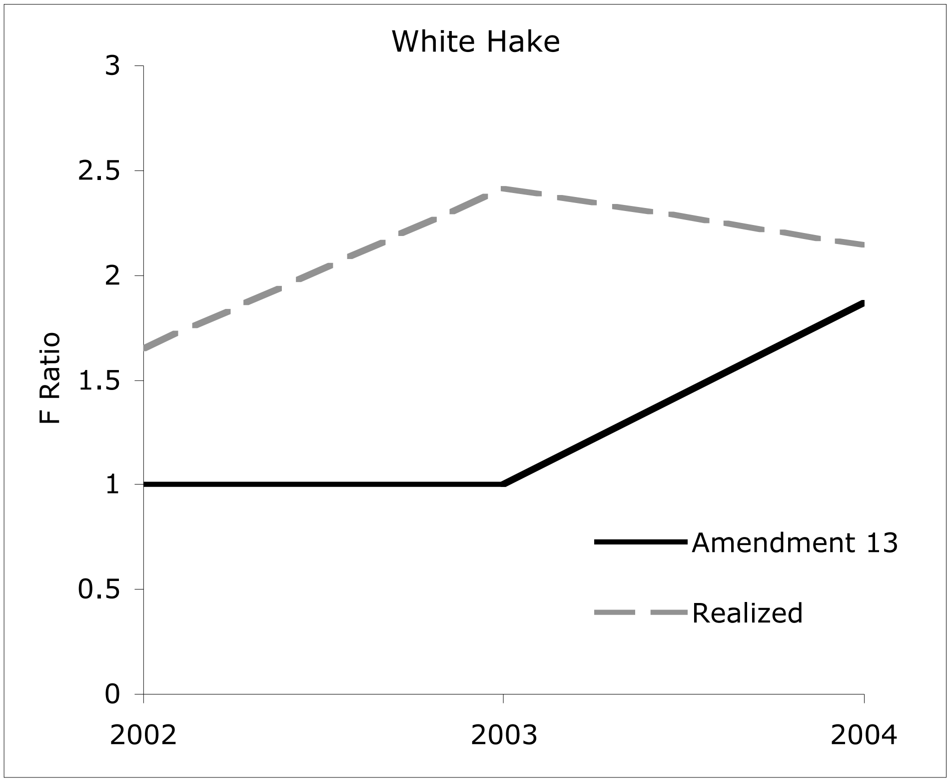

Figure 26e. Amendment 13 specified F_{Ratio} (black line; NEFMC 2003) compared to the most recent estimates of F_{Ratios} (dashed gray line; NEFSC 2005b) from 2002 to 2004 for white hake. The 2002 and 2003 F_{Ratio} values from Amendment 13 were "assumed" in stock projections, where the 2004 F_{Ratio} is the target level for that year (NEFMC 2003).

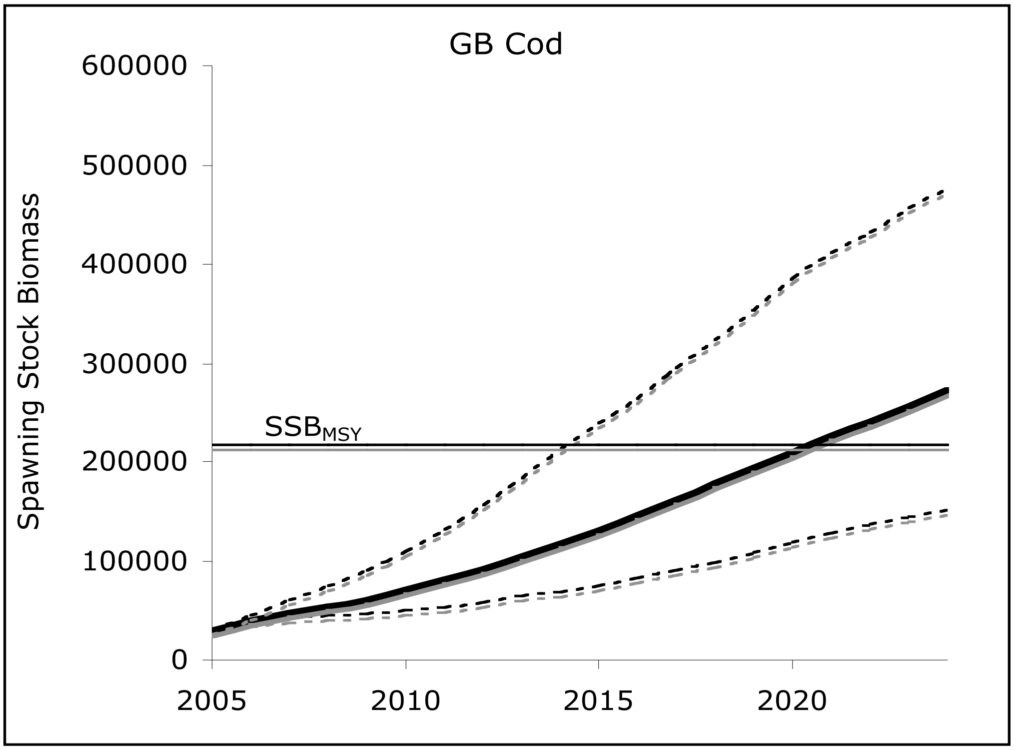

Figure 27a. Stochastic projections of GB cod SSB from 2005 to 2024 (the end of the rebuilding period). The solid black line represents the median level of stock biomass, while the dotted lines represent the 95% confidence intervals. Based on this projection, the stock has a 50% chance of crossing the rebuilding threshold (SSB_{MSY}) by 2021, and a 77% chance by 2024.

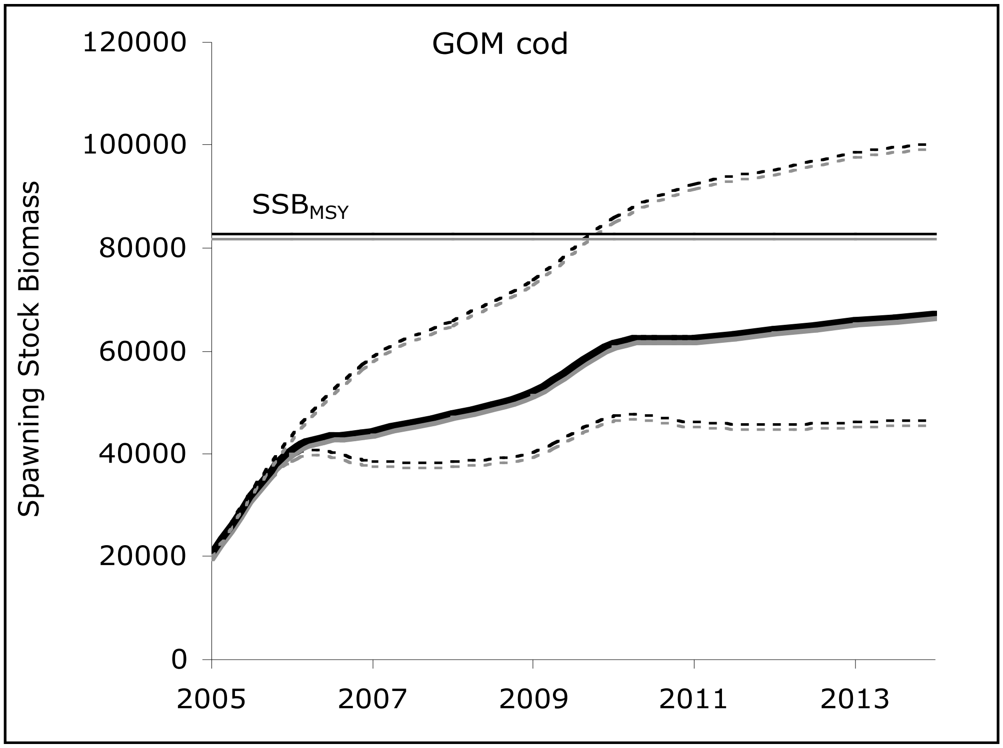

Figure 27b. Stochastic projections of GOM cod SSB from 2005 to 2014 (the end of the rebuilding period). The solid black line represents the median level of stock biomass, while the dotted lines represent the 95% confidence intervals. Based on this projection, the stock has a 15% chance of crossing the rebuilding threshold (SSB_{MSY}) by 2014.

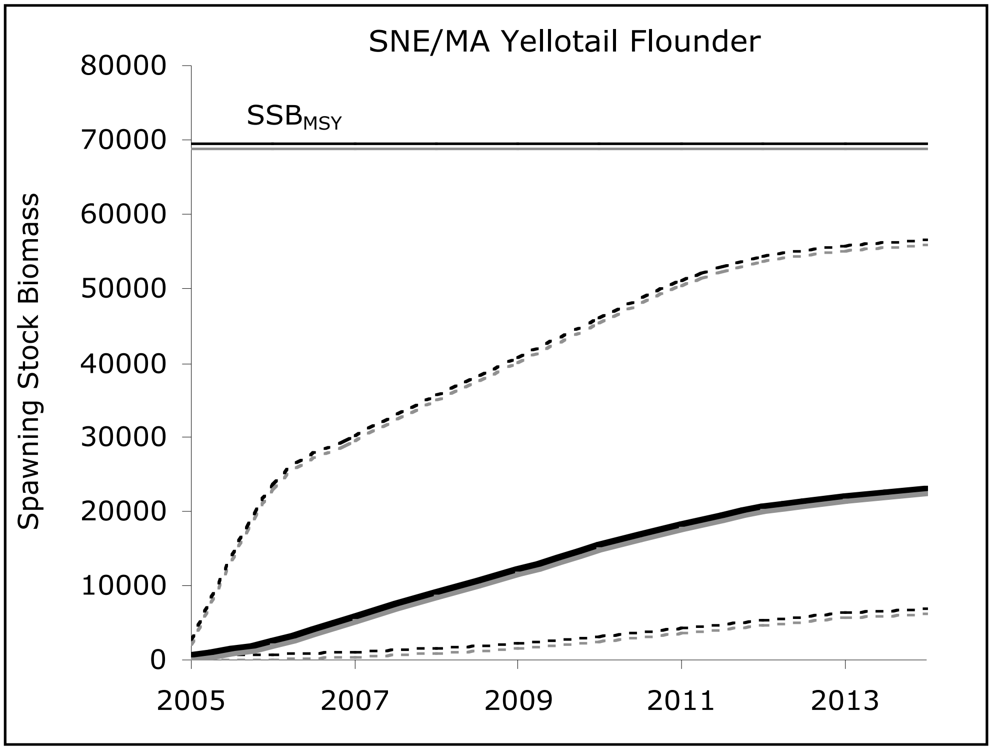

Figure 27c. Stochastic projections of SNE/MA yellowtail flounder SSB from 2005 to 2014 (the end of the rebuilding period). The solid black line represents the median level of stock biomass, while the dotted lines represent the 95% confidence intervals. Based on this projection, the stock has a 0.05% chance of crossing the rebuilding threshold (SSB$_{MSY}$) by 2014.

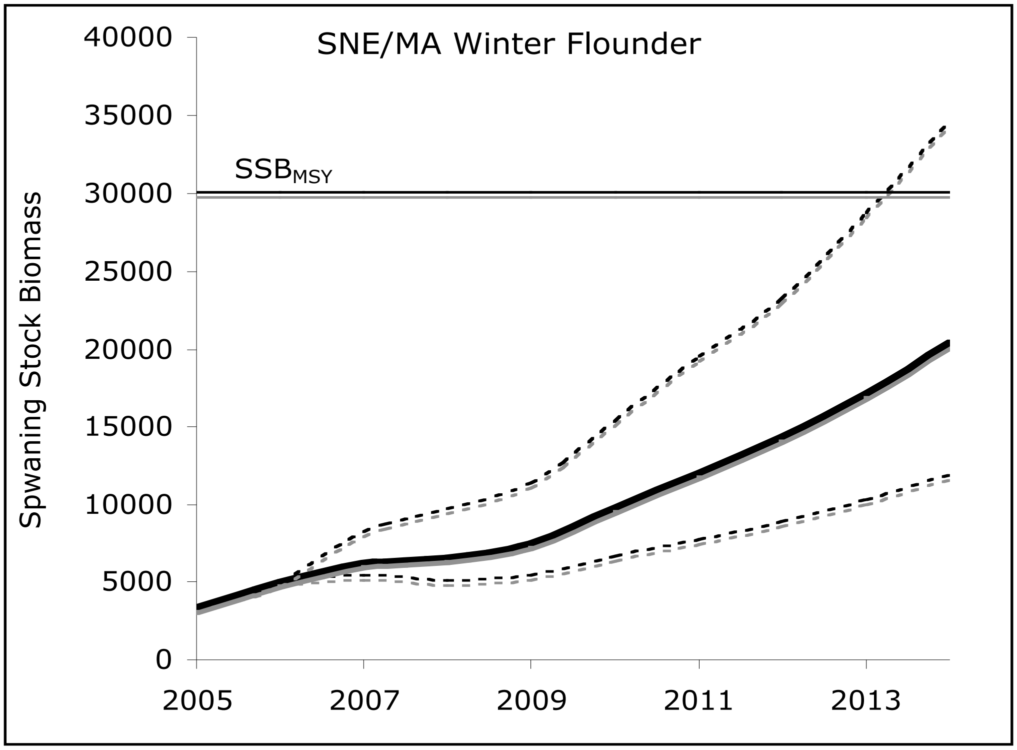

Figure 27d. Stochastic projections of SNE/MA winter flounder SSB from 2005 to 2014 (the end of the rebuilding period). The solid black line represents the median level of stock biomass, while the dotted lines represent the 95% confidence intervals. Based on this projection, the stock has a 7.8% chance of crossing the rebuilding threshold (SSB_{MSY}) by 2014.

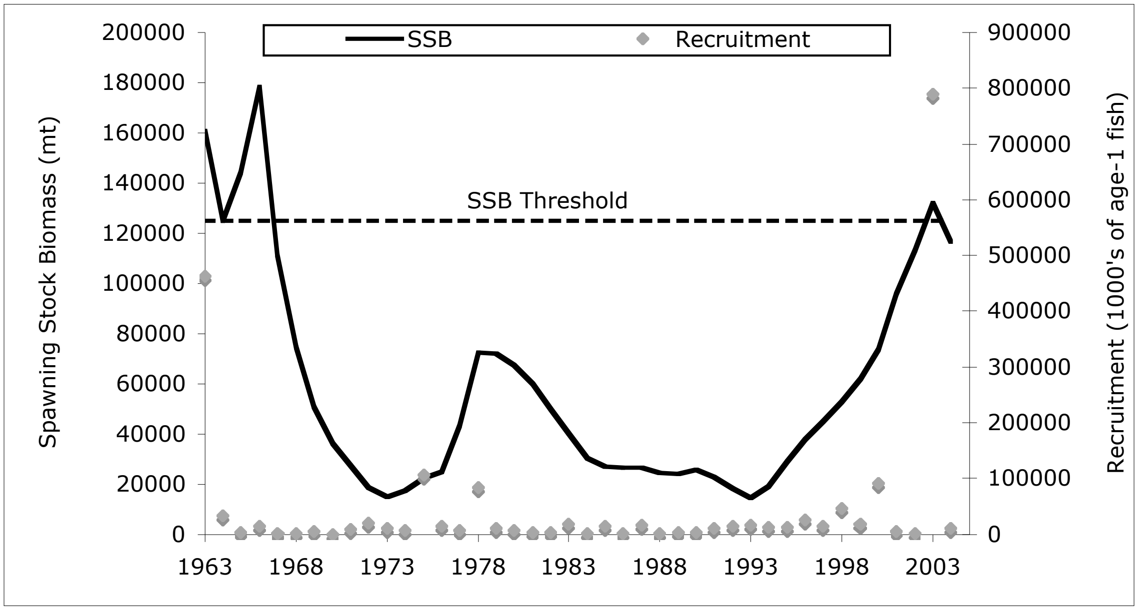

Figure 28a. GB haddock SSB (black line) and recruitment (grey diamonds) from 1963 to 2004. Recruitment of GB haddock is steady except for a few remarkably strong year classes that results in sharp increases in the stock SSB. Note that the 2003 year class is the largest in the time series, and may likely cause the stock SSB to cross the recovery threshold.

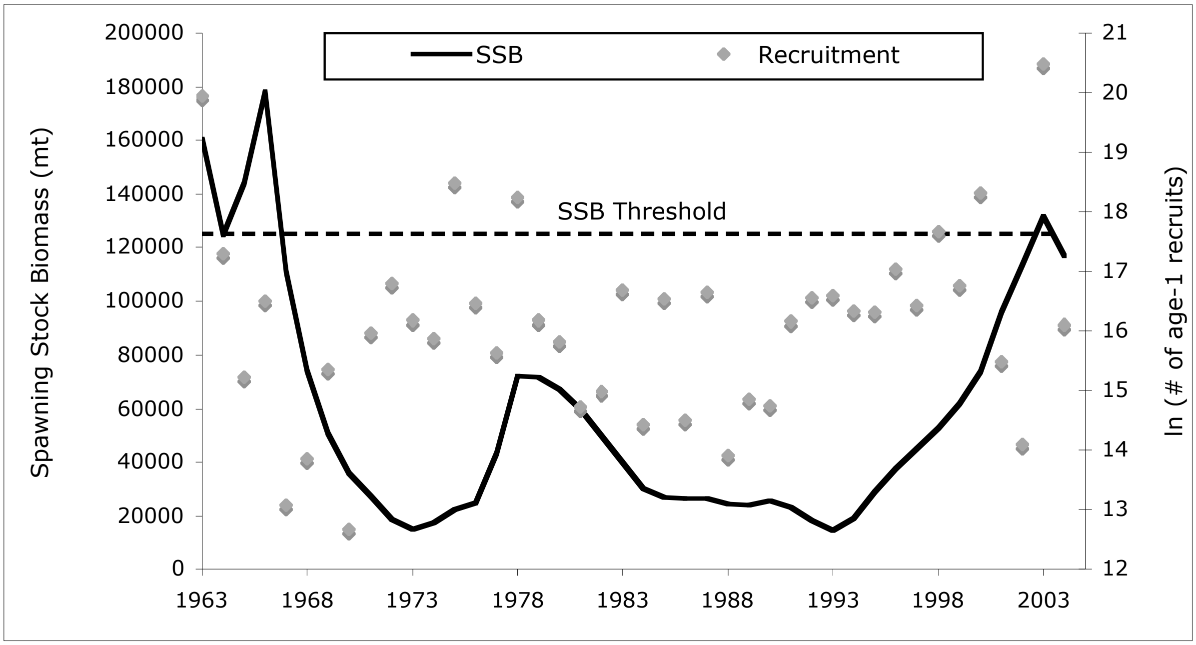

Figure 28b. GB haddock SSB (black line) and recruitment (gray diamonds) from 1963 to 2004. Recruitment is log transformed to show the variation in smaller recruitment events that is obscured in Figure 29a.

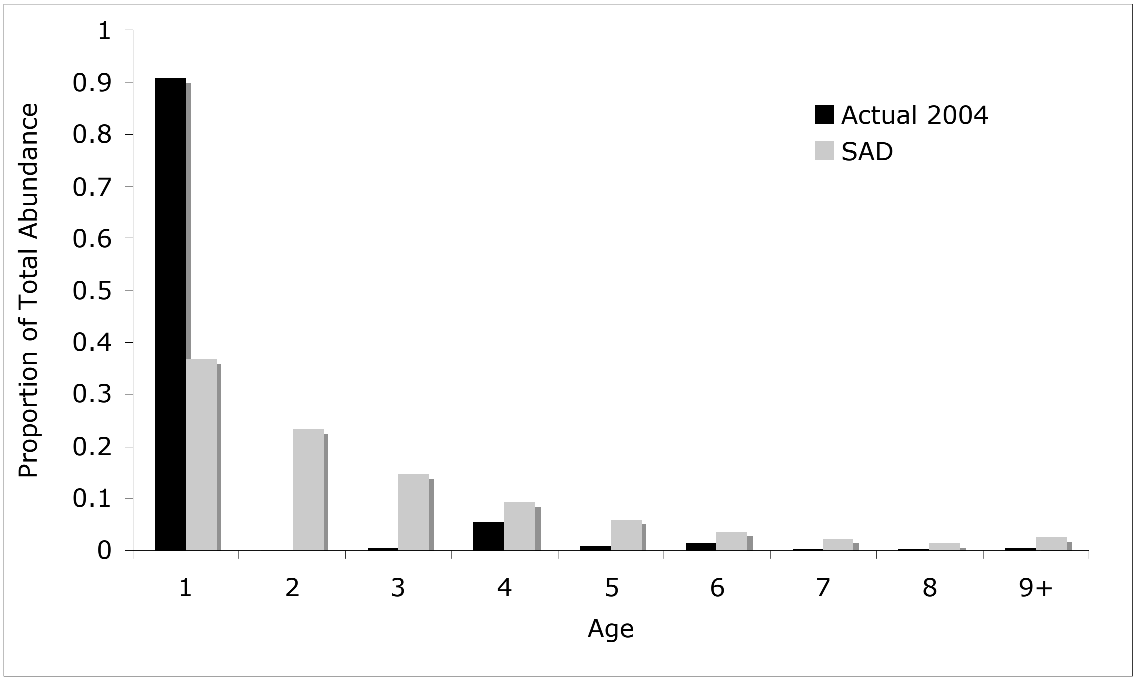

Figure 29a. Proportion of 2004 abundance of GB haddock by age class (black bars) and the proportion predicted if the 2004 population were in the stable age distribution (gray bars).

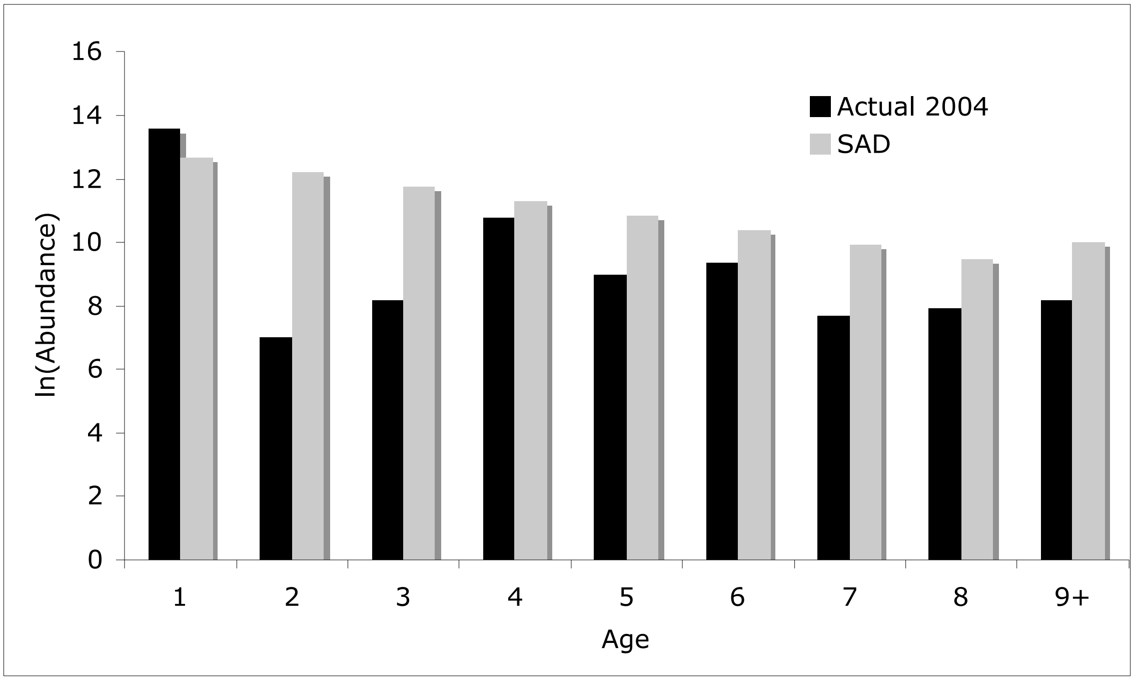

Figure 29b. Log-transformed abundance by age class of the 2004 stock of GB haddock (black bars) and the abundance predicted if the 2004 population were in the SAD (gray bars). The data are log-transformed because many of the differences in each age class are obscured in Figure 30a.

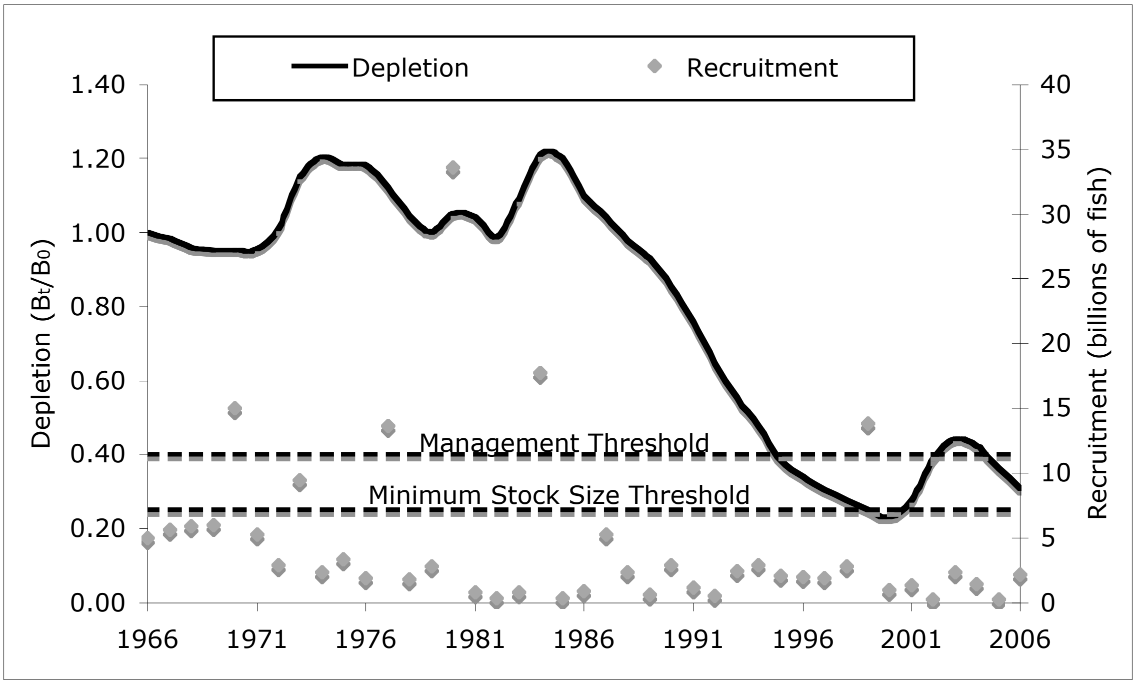

Figure 30a. Depletion (black line) and recruitment (grey diamonds) of Pacific hake from 1966 to 2006. Depletion is the ratio of biomass at time t (B_t) to the first biomass in the time series (B_0), which in this case is the biomass estimate from 1966. A depletion level of 0.4 is the management threshold (the rebuilding target). A depletion of 0.25 is the minimum stock size threshold (the overfished threshold; Helser et al. 2006).

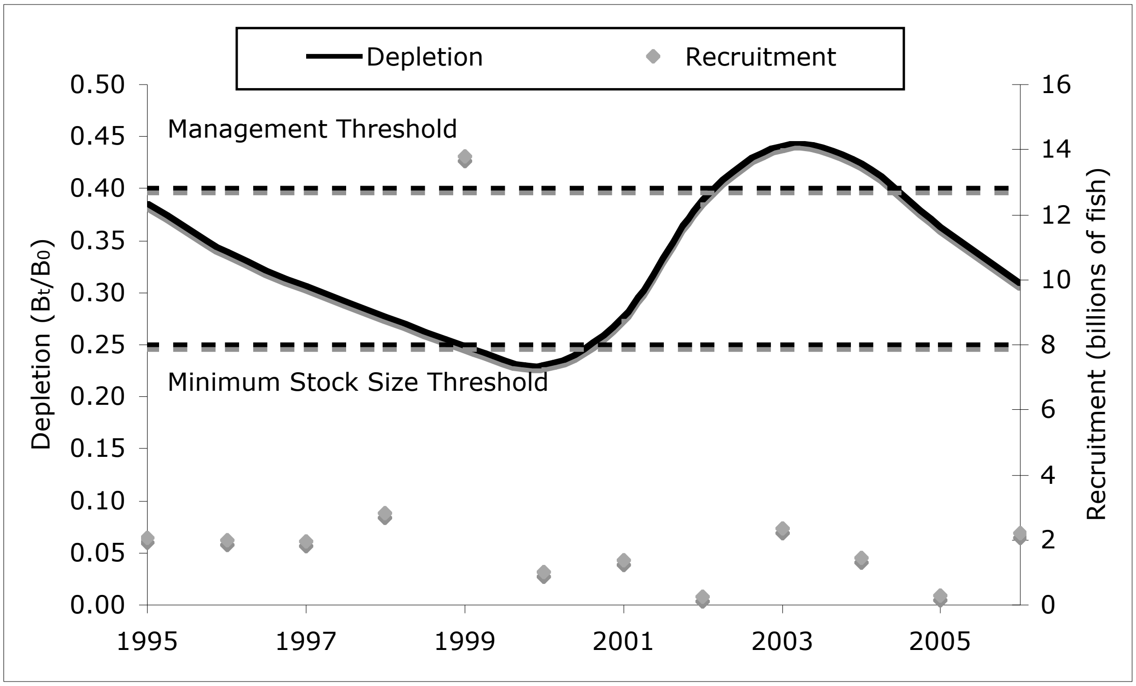

Figure 30b. Depletion (black line) and recruitment (gray diamonds) of Pacific hake from 1995 to 2006 (Helser et al. 2006).

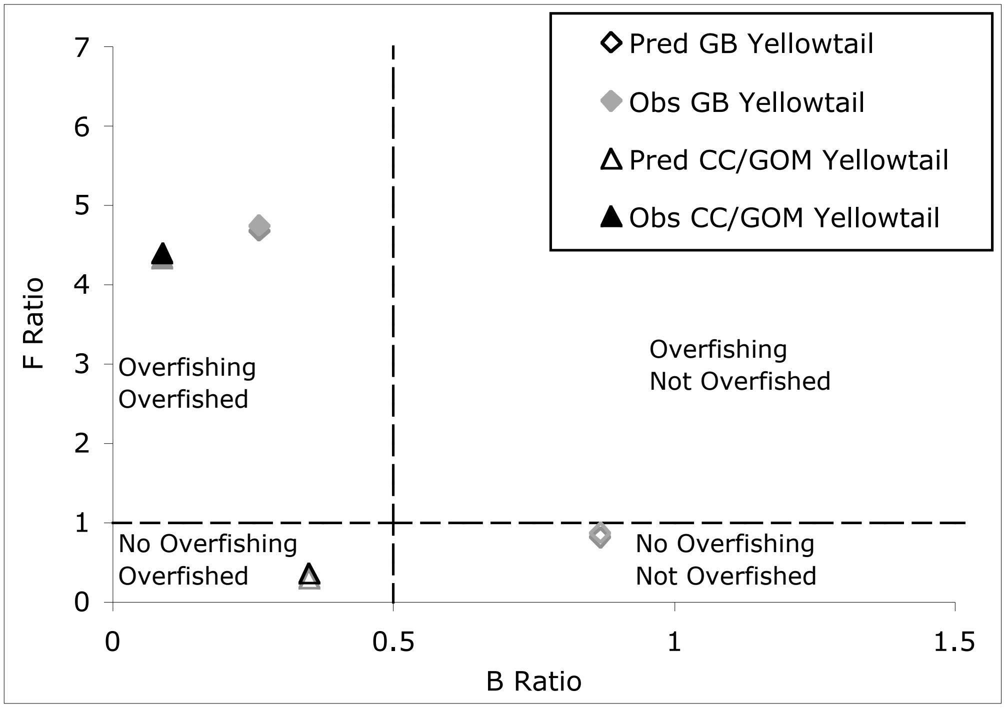

Figure 31. Predicted and observed 2004 status of GB yellowtail flounder and CC/GOM yellowtail flounder. The horizontal line represents the overfishing threshold and the vertical line represents the overfished threshold. GB yellowtail flounder was projected to be no longer overfished without overfishing (open gray diamond), but the most recent assessment indicates that it is both overfished with overfishing occurring (closed grey diamond; NEFSC 2005b). Similarly, the CC/GOM stock of yellowtail flounder was projected to be overfished without overfishing (open black triangle) but is actually overfished with overfishing (closed black triangle; NEFSC 2005b).

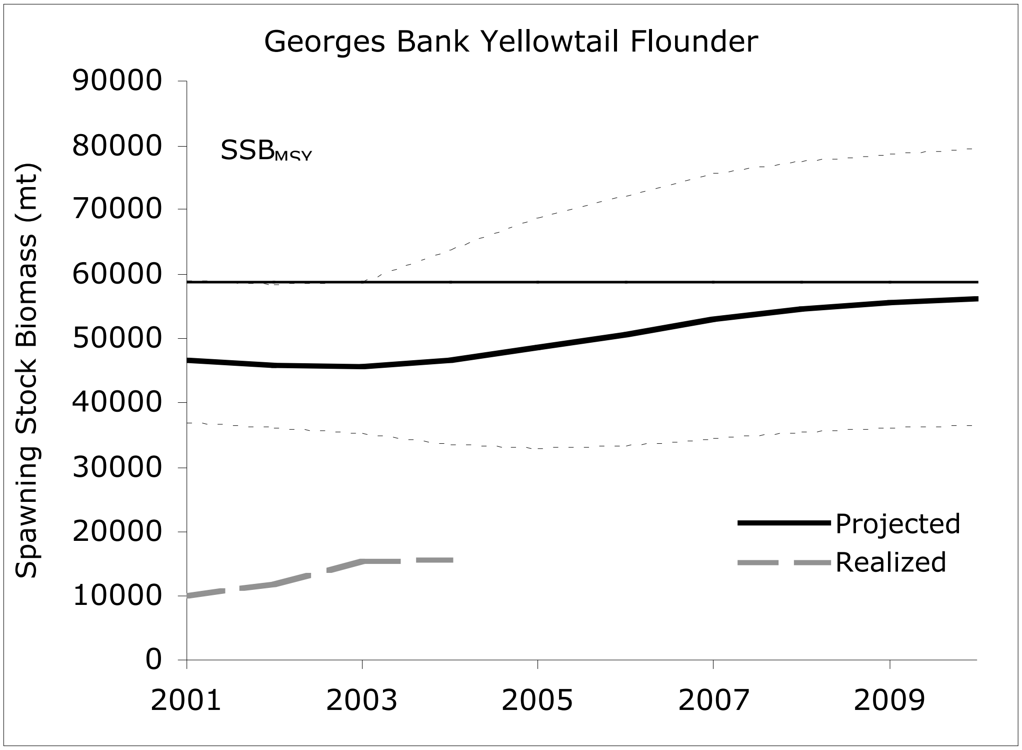

Figure 32. Projected (black line) and realized (dashed gray line) GB yellowtail flounder SSB. The projected values are from NEFSC (2002b) while the realized values are from NEFSC (2005b).

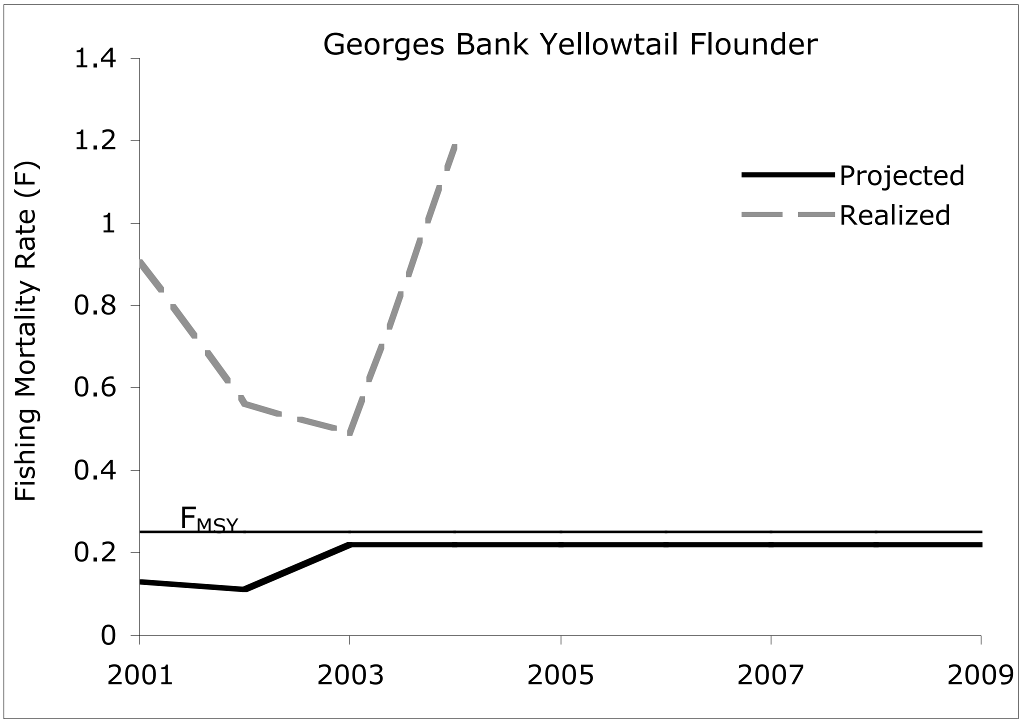

Figure 33. Projected (black line) and realized F values (dashed gray lines) for GB yellowtail flounder. Projected F values are those specified in NEFSC (2002b), realized values are from NEFSC (2005b).

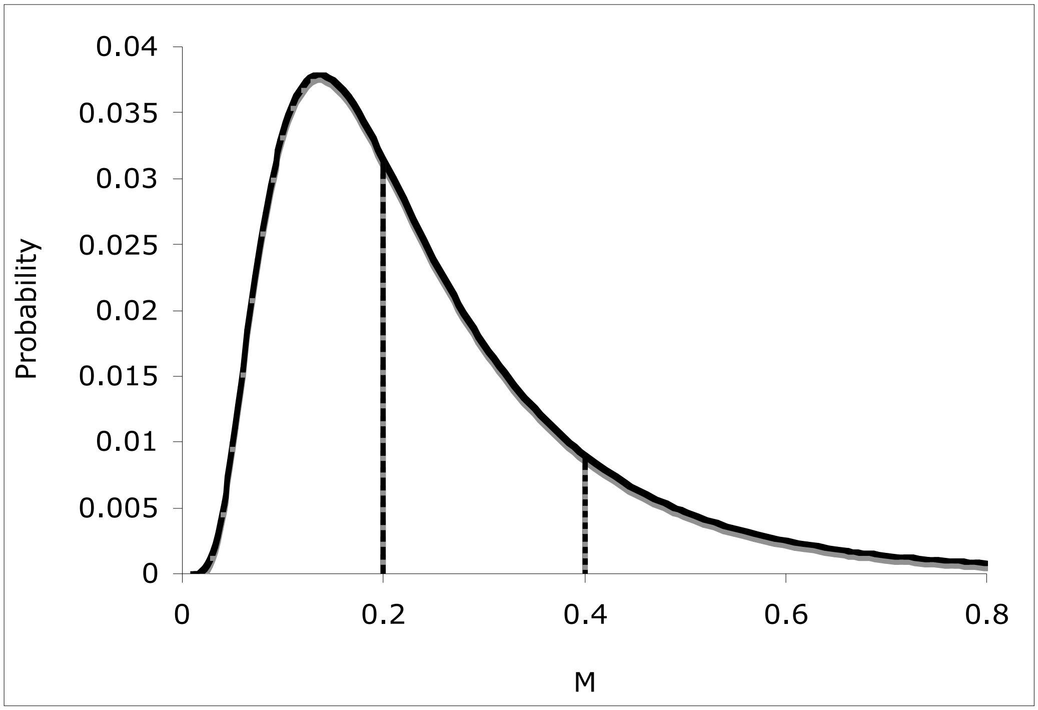

Figure 34. An example of a probability distribution for the natural mortality parameter M. In many assessments, M is often assumed to be fixed at 0.2. However, the true value of M may be somewhere in range of 0 to 0.8. For this distribution, the probability that M > 0.2 is 50%, while the probability that M > 0.4 is approximately 14%. Assuming a value of 0.2 when the true value is different is an example of observation uncertainty, and may strongly impact assessment results, rebuilding trajectories and management reference points.

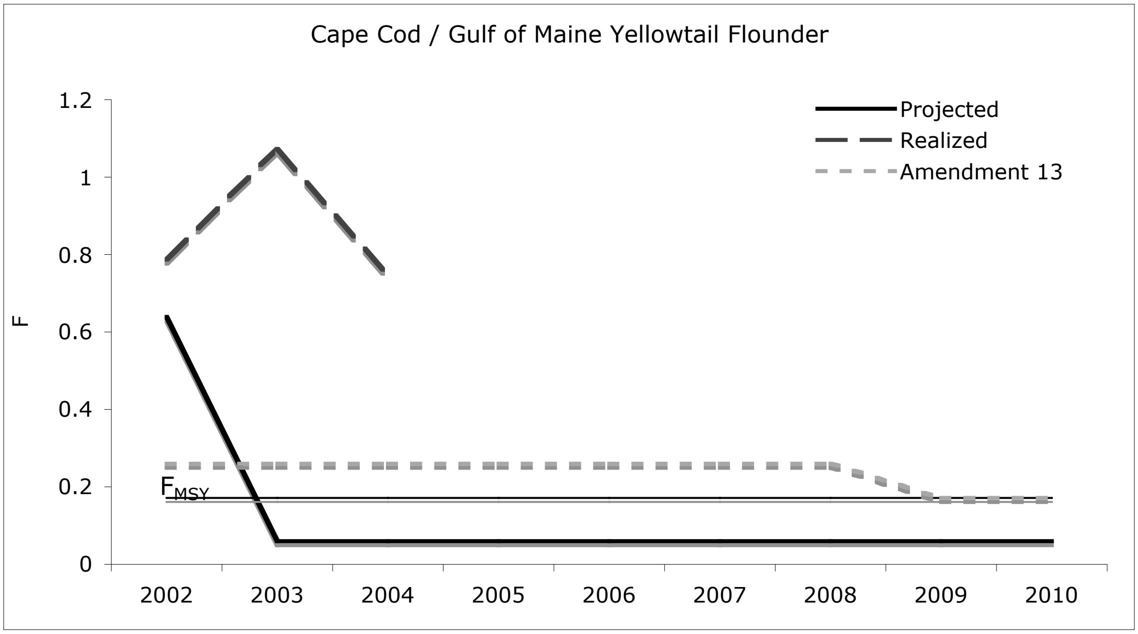

Figure 35. Projected (black line), realized (dashed dark gray line) and Amendment 13 specified (dotted light gray line) F values for CC/GOM yellowtail flounder. Projected values are those estimated by Cadrin and King (2003) that allow for rebuilding by 2009. Realized values are from NEFSC (2005b) and Amendment 13 values were taken from NEFMC (2003).

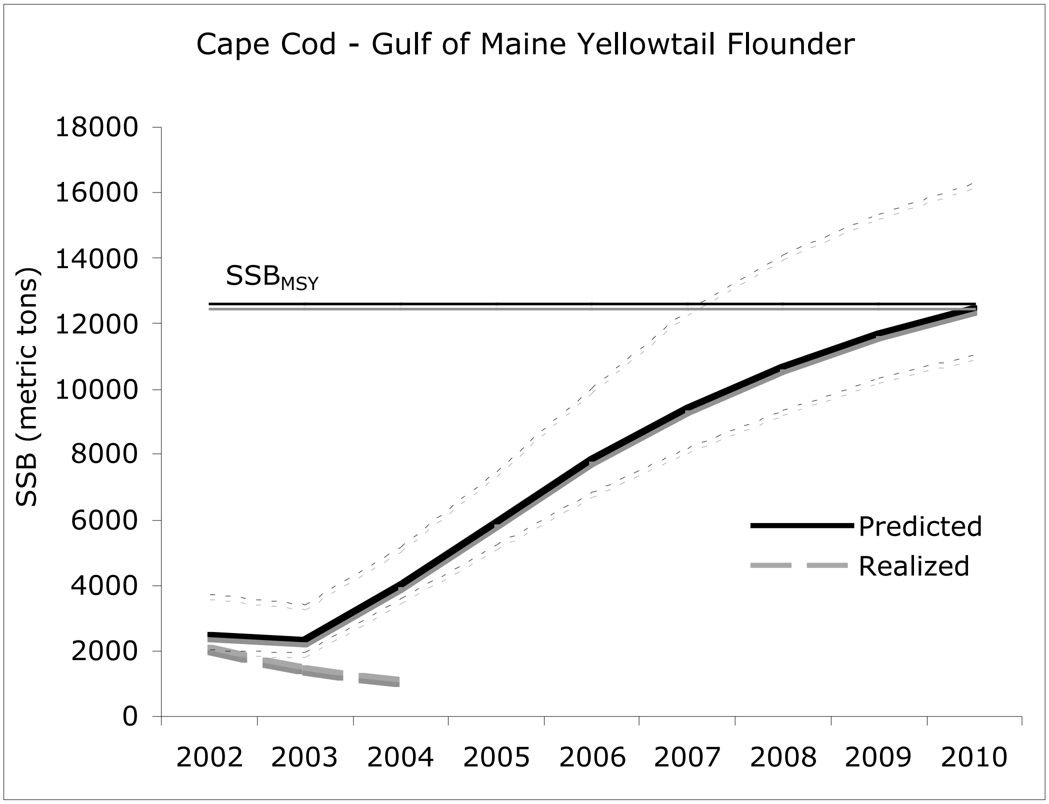

Figure 36. Projected (black line) and realized SSB of CC/GOM yellowtail flounder (dashed gray line). Thin dotted lines represent 95% confidence intervals for stock projections. Projected levels are taken from Cadrin and King (2003) and realized levels are from NEFSC (2005b).

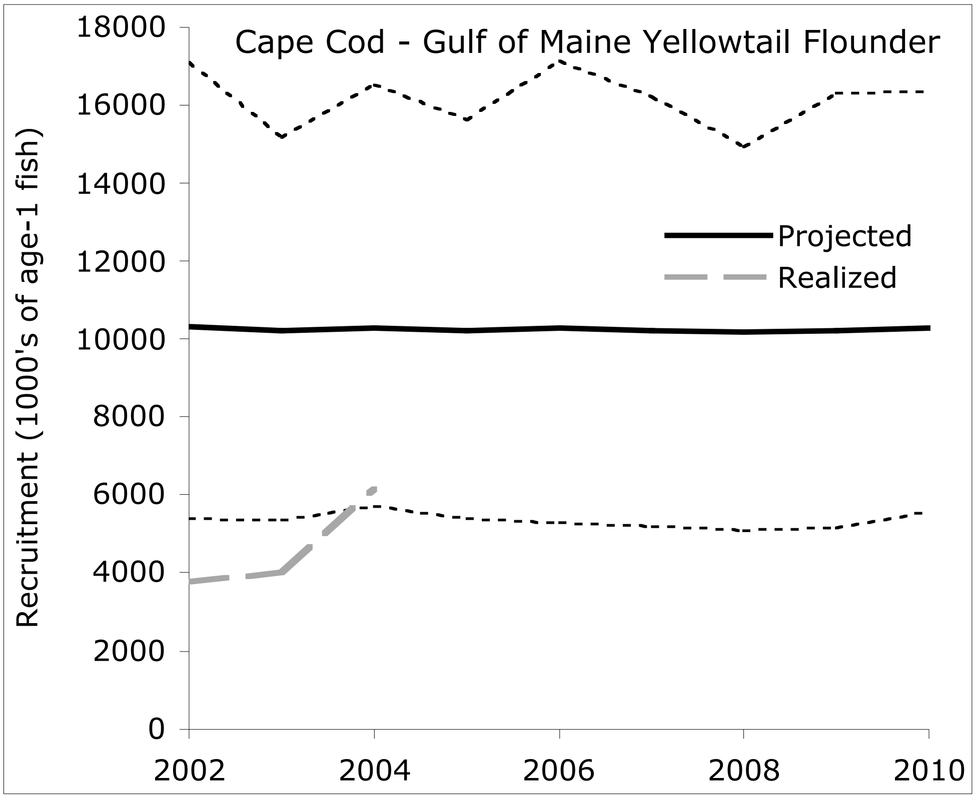

Figure 37. Projected (black line) and realized recruitment (dashed gray line) of CC/GOM yellowtail flounder. Dotted black lines represent the 95% confidence intervals for recruitment levels used in the stock projections in Cadrin and King (2003). Realized recruitment levels are from NEFSC (2005b).

LENFEST
OCEAN
PROGRAM

1025 F Street NW, Suite 900, Washington, DC 20004
ph: 202.552.2131 • fx: 202.552.2299
email: info@lenfestocean.org
www.lenfestocean.org