

A review of the theory, application and potential ecological consequences of $F_{40\%}$ harvest policies in the Northeast Pacific

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Introduction

The current management paradigm for marine fisheries in the United States, and indeed throughout most of the world, is that exploited fish and shellfish populations are capable of sustaining a long-term harvest as a result of compensatory population dynamics. Compensation occurs through density dependent processes such as growth, survival, and reproduction, where the rates of these processes increase as a result of declines in population density. Compensatory production can also be defined as surplus production in a single-species context, in which populations at abundance levels below their (generally theoretical) carrying capacity are capable of both growing at faster rates and producing more young, or recruits, than is necessary to maintain the population. Compensatory processes are varied, complex and often poorly understood (see Rose et al. 2001 for a thorough review). Nevertheless, the amount of compensation, or surplus production, in a given population can be estimated with population data and models. Although the models themselves are often extremely complex, most of the assumptions behind these models are not, and they can be traced back to the early development of population theory upon which most of contemporary stock assessment methods are based.

Both the FAO Code of Conduct for Responsible Fisheries and the UN Straddling Stocks Agreement, as well as the Magnuson-Stevens Fishery Conservation and Management Act in the U.S., call for stock-specific biological reference points to serve as limits, targets and performance indicators for management action when setting allowable fishing levels. The very earliest reference points were based on the maximum sustainable yield (MSY) of a given population and were estimated using the logistic growth curve. These curves generally predicted that populations were most productive when fished down to approximately half of their unfished, or equilibrium biomass. As population models became increasingly complex, it was found that MSY is actually quite difficult to estimate for most populations, thus 'proxy' reference points that were shown to lead to catches approximating MSY were derived with more readily available fisheries data and models. $F_{40\%}$, the fishing mortality rate that reduces spawning biomass per recruit (SPR) to 40% of its unfished level, is one of dozens of such points, and is the reference point most commonly applied as a target in North Pacific Fisheries.

MSY itself is a concept that has been painstakingly developed, intensely debated, and prematurely eulogized, and has ultimately evolved in a complex blend of language, mathematical theory and law. The essence of the concept can be distilled down to the premise that humans want the most that we can get from a resource over time. The premise behind this concept is that there are estimable levels of surplus production that may be safely removed from a given population. It has long been assumed that fish stocks and populations, and subsequently the ecosystems in which they exist, are healthy if they are maintained close to the levels that provide MSY. However there is a growing body of ecological, genetic and theoretical evidence that suggests that this may not necessarily be so, for neither all exploited species nor the ecosystems in which they exist. Measurement errors leading to poor management decisions, impacts to food webs, consequent changes to the life history of the target species, and large-scale variations in productivity associated with climate variability all complicate efforts to remove ‘as much as we can’, often leaving stocks, and increasingly ecosystems, in jeopardy.

The fishing mortality rate (generally denoted by “F”, as opposed to the natural mortality rate “M”) which reduces the spawning potential of a stock to 40% of its equilibrium level, $F_{40\%}$, was originally chosen as a proxy reference point for F_{MSY} where the latter could not be directly estimated. This was because simulations suggested that it resulted in yields very close to MSY, with comparable but generally lower fishing mortality rates, although fishing mortality rates could be greater than or less than F_{MSY} depending upon the life history of the target species. The purpose of this paper is to review the basic mathematical and ecological premises behind $F_{40\%}$ and other biological reference points, taking into consideration how alternative reference points measure up against each other, what some of the key shortcomings behind both the theory and application might be, and how management of North Pacific fisheries rate with respect to these insights. The purpose is not meant to argue whether $F_{40\%}$, or any other biological reference point (BRP) is either appropriate or flawed, nor to contend that reference points in general are or are not appropriate tools for managing fisheries. Such opinions are essentially value judgments dependent upon the priorities, objectives and opinions of stakeholders with very different perspectives. Instead, this paper is meant to synthesize the voluminous literature regarding the strengths and shortcomings of $F_{40\%}$ and similar reference points, with the hope that readers will better understand the theory, science and potential consequences of applying reference points as management tools for fisheries in the North Pacific and elsewhere.

The review is essentially composed of these four sections:

- Review the basic mathematical and ecological principles which led to the development of fish population modeling and biological reference points, particularly the evolution of $F_{40\%}$ and other reference points over time.
- A comparative look at commonly applied reference points, to examine how alternative BRPs measure up to each other with regard to both their inferences and assumptions, and a brief evaluation of alternative management strategies.
- Identification of some of the assumptions and potential shortcomings of reference point based management; such as the role of various types of error and uncertainty, potential evolutionary and demographic impacts that result, and the interactions between climate and other components of the ecosystem that may act or interact in unpredictable ways.
- Evaluate the application of $F_{40\%}$ in the fisheries managed by the North Pacific Fishery Management Council (NPFMC); particularly with respect to the question of whether $F_{40\%}$ is a conservative management strategy from both a single species and ecosystem perspective.

All of these sections are intended to be equally comprehensible to both scientists familiar with the theory and those without the mathematical background for entertaining these concepts, although unavoidably this may not always be so. However this is not meant to be a review of the quantitative roots of reference points, instead the concepts will be primarily descriptive. As in any review, an exhaustive (yet unavoidably incomplete) search through the relevant literature reveals an enormous volume of carefully written and thoughtfully executed work over the years, and anyone interested in following themes in greater depth should find that it points them in the direction of the resources most relevant to their particular interest.

1 The Origins of Fisheries Theory and Reference Points

The early development of various theories regarding fisheries and compensatory production, and the basic evolution of fisheries science in general, has been most thoroughly accounted in Smith (1994), a book highly recommended to anyone wishing to understand the context in which fisheries science developed. Ricker (1977), Beverton (1998) and Caddy (1999) also provide informative accounts of the chronology behind the development of many aspects of fisheries science as well, their works are especially relevant and insightful as these three authors have collectively spent well over a century as leaders in the field of fisheries science. Caddy (1999) also includes particularly relevant diagrams tracing the origins of the three major schools of thought in stock assessment. Among the most significant papers in the evolution of the contemporary fisheries theory are Schaefer (1954) Beverton and Holt (1957) Ricker (1958) and Larkin (1977); the latter essay (“An epitaph for the concept of maximum sustained yield”) is an important milestone in the progression of reference points based fisheries management. In evaluating the theory that is the basis for most fisheries science, it is revealing to discover that those who derived these methods were by no means oblivious of potential flaws, but more often than not prescribed considerable caution to users that they be highly conscious of such assumptions. While this review is limited to only a general overview of the historical literature relevant to the understanding of the origins of $F_{40\%}$, such a summary is essential reading to anyone who wishes to understand fisheries reference points in the context of how they have developed.

1.1.1 The Origins of Fisheries Population Theory

One of the most important developments in the field of fisheries science was the acknowledgement that variation in recruitment and age structure was a significant factor in estimating the productivity of marine populations, which was derived from Hjort’s (1914) description of variable year class strength in North Sea herring. Hjort demonstrated that year-class size was not a simple function of egg production but rather a result of differential multiple causes of mortality in early life history stages. He went on to offer two potential explanations for this differing mortality; the first being the availability of adequate food resources (the timing and

magnitude of plankton blooms) during the critical period in the early life history stages of larvae and the second related to the vagaries of ocean currents and the potential for the planktonic early life history stages to drift away from their appropriate habitat and thus not survive or contribute to the population. These two explanations formed the basis on which virtually all mechanisms of variability of recruitment in fish populations have been founded.

Equally significant were the observations of Huntsman and Baranov (whose papers were published independently in 1918, and are cited and summarized in Ricker 1977), who demonstrated that fisheries alter the age structure of populations. In particular, these results demonstrated that in the early years of any fishery, larger catches could be made than would be expected once the population reached equilibrium; this phenomena is still referred to as the ‘fishing up effect’ that accounts for nostalgic accounts of large, easily caught fish that exist in nearly any fishery (Ricker 1977). Concurrently, a sequence of growth relationships published near the turn of the century culminated in the now universally accepted growth curve derived by Von Bertalanffy (1938). An important characteristic of this growth curve is that younger fish have more rapid growth rates than older fish, and herein lies a piece of the theory of fishing; compensatory population growth results in part from a population being transformed into one of younger, faster growing individuals. Russell (1931) integrated these concepts with population theory, the thesis of his work being that a population could remain in steady state if population increments balanced population removals. More importantly, he was amongst the first to carefully and quantitatively deconstruct the factors that shaped population dynamics; namely recruitment, growth, natural mortality (predation or disease) and mortality resulting from fisheries. However as Punt and Smith (2001) recall, Russell also included in this analysis a caution that although the objective of fisheries science was to maximize yield while maintaining stocks, the “ideal of a stabilized fishery yielding a constant maximum value is impractical.”

Michael Graham was another of the early fisheries researchers to follow up on the logical connection between changes in population structure and yield. His ‘great law of fishing’, developed throughout the 1920s and 30s, was based the observation that following the end of the first World War (during which fishing on the high seas was greatly reduced), catch per unit effort in Northern European fisheries averaged nearly double that immediately prior to the war. As the post-war catch rates declined, Graham (1935) concluded that ‘as the fishing power increases the

stock falls, but the yield at first rises. Later... it ceases to rise, and that creates the main problem of fishing” (as cited in Smith, 1994). Graham then quantitatively told the story of North Sea fish populations since 1913, using a sigmoid curve (the logistic equation) to represent the total size of the stock in weight and a dome-shaped curve to represent the rate of change in yield relative to changes in effort. During this same period, W. Thompson was working with some of the best fisheries data of the time, from the Northeast Pacific halibut fishery, and developed very similar concepts in production theory. Importantly, Thompson’s work included methods to predict changes in catches that would be likely to result from changes in fishing effort. Thompson’s validation of this theory, as a result of observed increases in catch per unit of effort (CPUE) in the halibut fishery following effective effort controls implemented by the International North Pacific Halibut Commission, paved the way for applied fisheries science. However it is Graham who is generally credited with deriving the first surplus production model.

The development of conceptual models that explained the relationship between spawners and recruits was the next major achievement in fisheries science. As chronicled in Smith (1994), Herrington (1941) is one of the founding fathers of spawner-recruit theory. His early work used years of observations from the New England haddock fishery to conclude that scrod (young haddock) catches tended to be low when market (adult) haddock catches were both at high and low levels, but when market catches were intermediate in size, scrod catch rates tended to be higher. Herrington’s explanation for this observation was that at low adult population sizes, the production of recruits increased with an increase in abundance of spawning adults, while at high population sizes recruitment declined as a result of competition between adults and juveniles for prey. Thus the optimum conditions for recruits tended to be between low and high levels of adult abundance. Although this work was amongst the earliest to recognize the significance of the relationship between adult biomass and recruits, William Ricker is generally recognized for the first formal study of the mechanisms responsible for the relationship between stock and recruitment in his studies of salmon populations in British Columbia (Cushing 1977). In his models, Ricker (1954) assumed that levels of recruitment for Fraser River sockeye salmon were a function of both density dependent and density independent processes, and his equation for the stock-recruitment curve included substantial compensatory behavior at low and middling stock sizes, with reduced recruitment at high stock sizes.

1.1.2 The Heyday of Fisheries Science

These are but a few of the many discoveries and theories that set the stage for understanding the complexity of the interactions between fish, their environment and the fisheries that developed upon them. While this was an extremely productive period, the ‘heyday’ of fisheries science is generally considered to be the post World War II era. Ricker (1977) called this a period that ‘crackled with new information and new ideas. The solidification of the concept of MSY, its application to fisheries here, there, and everywhere, was just under way’. Similarly, Beverton (1998) recalled this period as a time when ‘We were carefree in the sense that we felt we were doing good and valuable things and, if we did not yet have all the answers, we were on exactly the right track to get them’.

Although the logistic growth curve had already been applied to fisheries problems by Graham, Thompson and others, Benny Schaeffer and other researchers involved with managing the Pacific sardine fishery in the West coast of the U.S. derived a novel application of the logistic to develop a surplus production model to describe the interaction between the sardine population and the fishing industry. Applying this model to the data, they suggested that there was an approximately 600,000 metric ton limit to sardine catches; additional effort in the fishery when yields were close to this level simply spread the landings out amongst more participants (Figure 1.1, based on Schaeffer et al. 1954). Although even these catch levels ultimately proved to be unsustainable, Schaeffer refined his work with methods for estimating surplus production for other stocks, fitting logistic equations as functions of population productivity for Pacific halibut and yellowtail tuna, and finding that for any given level of fishing effort there was a population size that would just balance the catch.¹ Ultimately his methods provided a means of estimating the level of fishing effort that would produce what he called the maximum sustained yield (MSY) which concurrently allowed fisheries biologists to arrive at a definition of overfishing; which was “fishing so hard that the total sustainable yield begins to decline” (Schaeffer 1954).

¹ Although the inferences of Schaeffer’s work with respect to the productivity of the California sardine stock were ultimately overly optimistic, likely as a result of the varied effects of climate on sardine productivity, these surplus production models actually did seem to work quite well with respect to modeling potential yields from many tuna and tuna-like fishes as well as many flatfish populations. This is actually quite consistent with the views of Longhurst (1998 and 2002; discussed further in section 3.3), who suggests that the consequences of recruitment variability in temperate waters leads to a lack of predictability with respect to population production which is not as relevant to many tropical fisheries.

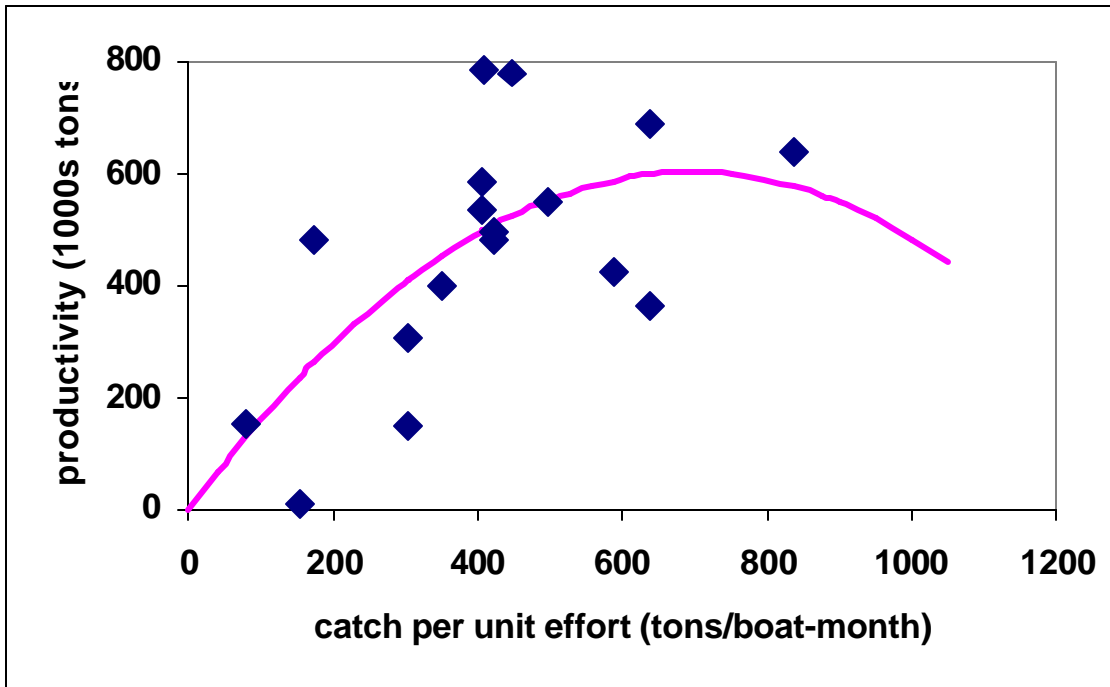


Figure 1.1: Schaefer’s (1954) illustration of the net productivity function (based on the logistic equation) of Pacific sardine, along with estimated productivity rates plotted against catch per unit effort (measured as tons of fish per boat per month) for the years 1932 to 1950.

This concept was revolutionary to fisheries, and the Schaeffer method was quickly applied to many heavily exploited populations, including fisheries for the great whales. The methodology remains somewhat used in many fisheries today, particularly in fisheries for which age data is unavailable or unreliable (Caddy 1999). However during this same period William Ricker’s (1954) work with salmon and other fish stocks had led to his observation that for all spawner-recruit relationships there existed an average spawning biomass that led to the maximum surplus reproduction between high and low spawning stock sizes. Consequently Ricker too arrived at a definition of MSY, which he later (Ricker 1975) defined as “the largest average catch or yield that can continuously be taken from a stock under existing environmental conditions”. More significantly, he noted that under conditions of fluctuating recruitment, particularly in species that spawned only once (semelparous species such as salmon), obtaining the maximum yield could require taking fewer fish in some years than in others. This notion of MSY as a dynamic, rather than a purely static value, persists in most definitions of MSY to date; for example in U.S. fisheries MSY is currently defined as “the largest long-term average catch or yield that can be

taken from a stock or stock complex under prevailing ecological and environmental conditions” (Restrepo et al. 1999).

Ray Beverton and Sidney Holt (1957) had also been working on spawner-recruit relationships and fisheries theory for Northeast Atlantic fisheries; their methods allowed a cohort² of fish to be followed throughout their life with age-specific growth, fishing and natural mortality interacting instantaneously in a series of equations that synthesized the earlier work of Russell, Graham, Ricker, Baranov and von Bertalanffy. Their work also provided a framework for estimating at each age of entry into a given fishery, the corresponding maximum sustained fishing mortality rate and subsequent yield under constant recruitment assumptions, which are the conceptual basis of yield per recruit models and reference points. Finally, it included an alternative to the Ricker stock-recruitment equation, one in which recruitment did not fall at high population sizes but rather stayed constant at high adult densities.

Because the nature of the spawner recruit relationship is so critical in fisheries, an example of the two most commonly used relationships, the Ricker and the Beverton-Holt, are presented as figure 1.2 using data from an Icelandic herring stock. Note that the essential difference between Ricker and Beverton-Holt functions is that the former predicts that at high population densities, recruitment will fall off; the latter predicts that recruitment will reach a carrying capacity and essentially remain unchanged with adult biomass at high stock sizes. The amount of compensation can be inferred by the distance between the predicted recruitment and the 1:1 replacement line. Thus, the Ricker curve infers more compensation at lower stock sizes, and stronger density-dependent processes limiting recruitment at high densities (such as cannibalism, disease or limited prey availability) than the Beverton-Holt. For comparative purposes, a truly density-independent spawner-recruit relationship would essentially be the straight (1:1) replacement line between spawners and recruits through the origin. True density independence thus implies that the number of recruits would depend solely on the number of spawners, in other words there would be no factors such as limited prey or habitat that would limit survival at high population sizes (Hilborn and Walters 1992). However density-independence is also commonly referred to for highly stochastic (variable) recruitment, in which recruitment events appear to be

² A cohort can also be defined as a year class, or as all of individuals in a given population of the same age. A “strong cohort” or “strong year-class” in a fishery generally refers to an abundance of individuals of the same age which may dominate both the population and the yield of a fishery over time.

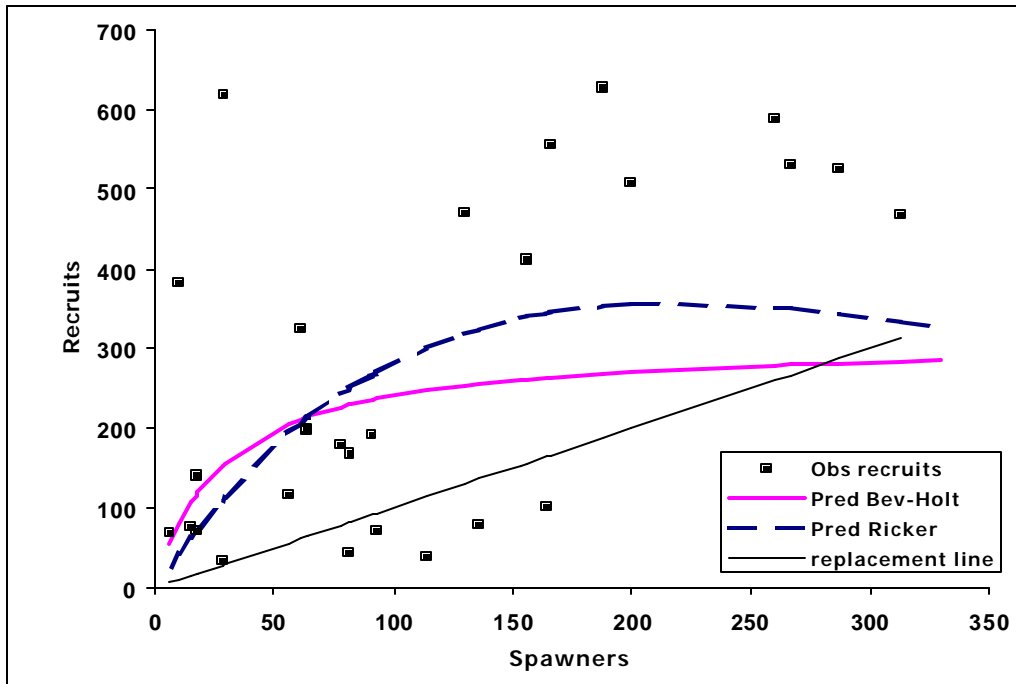


Figure 1.2: Comparison of Ricker, Beverton-Holt and replacement spawner recruit relationships for Icelandic Herring (adapted from Hilborn and Walters 1992).

wholly independent of spawning biomass and more a function of variable (or unknown) environmental factors.

The work of Beverton and Holt went far beyond an alternative to the Ricker spawner-recruit curve; it set the stage for a new era of population modeling using Virtual Population Analysis, or VPA. VPA is the technique by which catch at age data and estimates of natural mortality are used to reconstruct cohorts, and consequently total numbers and biomass of fish at all ages over the period for which data is available; and this remains the most commonly applied stock assessment method to date (Hilborn and Walters 1992). This technique quickly became the primary focus of fisheries science in the 60s and 70s, and management (especially in Europe) soon focused on using VPA results to determine fishing strategies that would maximize the yield per recruit; defined as F_{max} . The consequences of this approach to exploited populations quickly became apparent; for although the strategy integrated information regarding individual growth, natural mortality and vulnerability to various gear types it did not include any explicit

consideration for the proportion of fish remaining in a population that were capable of reproducing.

Cushing (1973) recognized this problem when he made the distinction between growth overfishing and recruitment overfishing. Cushing defined growth overfishing as catching fish before they have reached the point where losses from natural mortality are greater than gains from individual growth, while recruitment overfishing occurs when more fish are caught than can be replaced by the remaining spawners. Because VPA results provided sufficiently accurate population data from which researchers could evaluate the relationships between a population's spawning biomass (total biomass of mature females) and the number of recruits (the total numbers of fish at the earliest age of entry into the fishery) there was a continued search for reference points that could be aggressive with regard to total yield yet conservative with regard to ensuring sufficient spawning potential for future generations.

1.2 The Development of Fisheries Reference Points

As global landings increased and fisheries science continued to develop, the application of management strategies focused on maximizing yield and handbooks, algorithms and computer programs for doing so proliferated. Most of this work focused on estimating maximum sustainable yield (MSY) and the associated fishing mortality rate (F_{MSY}) and biomass (B_{MSY}), or similar 'yield maximizing' reference points such as F_{max} . MSY itself was quickly enshrined in both international and national agreements and laws worldwide, Punt and Smith (2001) include the Inter-American Tropical Tuna Commission, the International Commission for Northwest Atlantic Fisheries and the North Pacific Fur Seal Commission, the International Whaling Commission as just some of the international bodies that adopted MSY as a management objective. In the United States the Fishery Conservation and Management Act of 1977 required that the regional fisheries management Councils adopt fishing strategies that would lead to the attainment of optimum yield, which itself was defined as MSY as modified by any relevant economic, social or ecological factor.³ The 1982 United Nations Convention on the Law of the

³ The Act was of course later renamed the Magnuson-Stevens Fishery Conservation and Management Act, and the 1996 Sustainable Fisheries Act amendments changed the word 'modified' to 'reduced' in the definition of optimum yield to prevent the adoption of fishing strategies that would exceed MSY; this change in language justifies the current application of MSY as a limit rather than a target.

Sea also stated that MSY was the stated objective of fisheries management. Many other national and international management agencies have since adopted MSY or other reference points as targets or limits (Gabriel and Mace 1999), and overall dozens, perhaps hundreds, of reference points have been and continue to be derived, debated and applied in fisheries throughout the world. Reference points have continued to be the focus of major workshops over the last two decades; major contributions include those edited by Kruse et al. (1992), Smith et al (1993), and Restrepo (1999).

Typically, three principle classes of reference points are described by fisheries scientists and managers; surplus production model reference points, spawner-recruit model reference points and dynamic pool (age structured model) reference points derived from age-structured models and accurate growth data (Sissenwine and Shepard 1987, Gabriel and Mace 1999). The latter is by far the largest category, one that initially focused on yield per recruit estimates such as F_{\max} , $F_{0.1}$ and over the last decade or so has evolved to include spawning biomass per recruit information such as F_{high} , F_{med} and $F_{40\%}$ as well as reference points that aim to avoid fishing mortality rates that would lead to severe depletion or extinction (such as F_{τ} and F_{crash}). As mentioned earlier, MSY and F_{MSY} can be derived with any of these classes of models, but Gabriel and Mace (1999) refer to dynamic pool model estimates of MSY as a separate class of extremely data-intensive surplus production models. These models require a functional stock-recruit relationship, a spawning-stock-biomass per recruit analysis and a yield per recruit analysis. However the data requirements for estimating MSY from an age structured model are substantial, and consequently applied management in the United States and elsewhere is typically based on proxies for MSY.

An additional class of reference point might be added, which are simply empirical reference points when little or no information is known about a stock, in which case targets or limits might be $F=M$ or some fraction of M (where M is the natural mortality rate), or simply based on historical catches or mortality rates. Alverson and Pereyra (1969) suggested that $F=M$ could be an appropriate strategy to attain yields close to MSY for poorly studied stocks in the Northeast Pacific, citing FAO working group results as a source. Although these methods were originally supported by little empirical evidence, subsequent modeling studies suggested that setting F approximately equal to M can be reasonable for some life history types, and this approach

remains in use for many data poor fisheries and assemblages in the North Pacific. A quick summary of each major class of reference point, and the basic characteristics of the associated models is found in table 1.1 below, and the description of reference points in the text approximately follows both the order of their development in the literature and the corresponding increase in data requirements.

**Table 1.1: Summary of Primary Classes of Reference Points
(adapted from Gabriel and Mace 1999)**

<i>Model Type</i>	<i>Example Reference Points</i>	<i>Model Characteristics</i>
No model- arbitrary	$F=M, F=0.75M$	may be used in data poor fisheries, assumes some knowledge of M and B!
Surplus Production	F_{MSY}, B_{MSY}	no age structure, no S/R relationship, use with caution!!
Spawner-Recruit	$P_s, u_s (\sim B_{MSY}, F_{MSY})$	no age structure, used primarily to set escapements (salmon, herring)
Dynamic-pool (yield per recruit)	$F_{max}, F_{0.1}$	age structured, assumes recruitment independent of spawning biomass
Dynamic-pool (spawner per recruit)	$F_{40\%}, B_{40\%} (F_{\%SPR}, B_{\%SPR})$ $F_{high}, F_{med}, F_{low}, F_{rep}$	age structured models, use S/R data, but no explicit S/R relationship
Dynamic-pool (production model)	$F_{MSY}, B_{MSY}, F_{crash}, F_{\tau}$	Uses age structured data and S/R curve to derive MSY and limit points

1.2.1 Surplus Production Model Reference Points

As suggested in the introduction, maximum sustainable yield (MSY) is a construct that is simultaneously mathematical, theoretical and legal. The most basic technical, or mathematical interpretation is that MSY is the peak of the surplus production curve, which is based on the application of the logistic growth curve as quantified by Schaeffer in 1954 although numerous alternative formulations of the production model exist (see Hilborn and Walters 1992, or Quinn and Deriso 1999). In its simplest form, the surplus production curve is simply the logistic growth model, in which growth, mortality and recruitment are combined into an intrinsic population growth rate (r) the value of which is dependent upon the ratio of the existing population to the population's carrying capacity (K).

The instantaneous equation is written as: $\frac{dB}{dt} = rB \left(1 - \frac{B}{k}\right) - C$ where $C = qEB$.

In this model, B is the Biomass, r is the intrinsic rate of population growth, k (or B_0) is the population at equilibrium (or carrying capacity), C is the catch rate, q is a catchability coefficient (or the fraction of biomass removed per unit of fishing effort) and E is the total amount of fishing effort. The resulting parameters of management interest are consequently quite simple to evaluate in this simple version of the model; MSY is simply $rk/4$, the stock size for MSY (or B_{MSY}) is simply $k/2$ (half the equilibrium stock size), the exploitation rate that leads to MSY (or F_{MSY}) is $r/2$ and the maximum rate of exploitation is r. For the model to be meaningful, there should be a substantial number of years of accurate catch and effort data; and users are cautioned that these models perform poorly unless the stock size has actually been reduced below B_{MSY} for some of the years considered. Additionally, these models will often fit the data equally well with low values of r and high values of K, as with low values of K and high r; thus without independent estimates of one or the other of these values the results of fitting such a model can be of very limited use.

An extension of this approach is that given catch per unit effort (CPUE) data, the model can also be calibrated to provide economic indices; for example the Maximum Economic Yield (MEY) is the point on the resulting curve where the maximum resource rents (or profits; the point at which total revenue minus total costs is the greatest) are obtained, and the open-access equilibrium is the point at which total fleet costs are equal to the total fleet revenue. Significantly the MEY is by definition always achieved at a lower fishing mortality rate than the open access equilibrium (Caddy and Mahon 1995). This dilemma leads to the trade offs inherent in managing fisheries for societal needs; whether it is more desirable to have greater profitability by maximizing economic rents or greater employment but reduced efficiency and profits in open-access scenarios.

Beyond fitting the models themselves, the significance of random or environmentally induced fluctuations in surplus production was one of the first conceptual flaws of the MSY concept (as applied in surplus production models, but certainly relevant to other derivations of MSY as well) to result in severe criticism throughout the fisheries community. The early assumptions were that if a fishing mortality rate of F_{MSY} was applied to a stock, the population would fluctuate

around B_{MSY} and the long-term average yield (MAY, maximum average yield) would be equivalent to MSY. However early work simulating simple population dynamics in the presence of fluctuating levels of surplus production suggested that this was not so; MAY tended to be significantly less than MSY under variable conditions. Doubleday (1976) in particular concluded that ‘in the presence of fluctuations in production, attempts to remove the MSY yield each year from a stock leads to disaster’; similarly May et al. (1978) found that ‘if harvesting inadvertently exceeds the MSY level; here high effort may produce low average yield with high variance.’ For these and other reasons (including the suite of problems associated with estimating CPUE in evolving fisheries without introducing biases in the data over time), the application of such models is generally frowned upon if adequate data for more complex models exists.

Although rarely used for contemporary stock assessment (at least in the United States) one interesting approach for utilizing surplus production models was recently published by MacCall (2002) who used the results of age structured models to fit ‘known biomass’ surplus production models and consequently evaluate the inferred maximum sustainable yield for many of the long-lived and slow growing west coast groundfish stocks. His results suggested that the prescribed harvest policies, $F_{35\%}$ and $F_{40\%}$, were too aggressive for most stocks, and provided alternative measures of MSY which were shown to be substantially lower than even recent ABC’s for many species. The inferences from this approach provided a unique perspective on the productivity of these stocks, forcing modelers and managers alike to confront and explain observed trends in biomass relative to exploitation histories. They also illustrated that despite the dominance of more complex age structured models in contemporary stock assessment, there is still an important role to be played by simple yet intuitive fisheries models.

1.2.2 Spawner-Recruit and Constant Escapement Reference Points

Direct estimates of MSY as a reference point can be theoretically derived based solely on density-dependent compensation as derived from the spawner-recruit relationship. The reference points associated with such relationships were presented by Ricker (1975) and include the B_{msr} (spawning biomass associated with the maximum surplus reproduction, P_s in Ricker’s notation), the replacement spawner abundance (where recruitment is equal to the parent stock, or the

intersection with the spawner-recruit curve with the 1:1 replacement line, called P_r by Ricker) and the exploitation rate at MSY (called u_s by Ricker). For any stock size greater than B_{msr} there should be an associated level of fishing mortality (F_{msr}) that would reduce the spawning biomass (or allow a set level of escapement for semelparous species such as salmon) that would result in B_{msr} . However given fluctuations in stock sizes, the fishing mortality rate must be changed annually to achieve this constant escapement of B_{msr} . Most salmon fisheries, and many fisheries for herring (which are typically fished in large spawning aggregations) are managed with such constant escapement policies, which are based on the observed spawner-recruit relationships.

For example, referring again to the two spawner recruit curves shown in figure 1.2 (page 12), the resulting inferred MSY is found at the point where the distance between the curve and the replacement line (the surplus recruitment) is the greatest. In this example, this point occurs with approximately half the spawners with the Beverton-Holt relationship as it is with the Ricker relationship (130 spawners with the Ricker versus 65 with the Beverton-Holt). Although the Beverton-Holt relationship offers a slightly better fit to the data (using a maximum likelihood function with log-normally distributed error), both models fit the data reasonably well and determining which of the two is appropriate for a given stock (and consequently what level of target spawning biomass or escapement is optimal) is a substantial challenge to any biologist or manager. In reality, the true shape or nature of the relationship may never be known, yet the differences in the assumptions regarding the shape of the relationship are substantial. Additionally, variability around any spawner-recruit relationship is typically quite large, and environmentally induced changes in the production of many species often leads to apparent changes in the spawner-recruit relationship that imply variations in productivity over longer time scales. However, as we will see this is certainly not a problem unique to this class of reference points, as nearly all contemporary reference points depend on assumptions about the nature of the spawner-recruit relationship.

Myers et al. (1994) described the challenges of understanding spawner-recruit relationships in a nutshell: “The relationship between spawning biomass and recruitment is notoriously variable and the underlying theoretical relationship is never known in practice... It is no simple task to estimate from empirical data a threshold below which recruitment is most likely to be poor”. Three general processes are among those that make conclusive inferences about spawner-recruit

relationships difficult; the model assumptions may be too simplistic biologically, variability caused by abiotic factors (such as climate) may mask underlying relationships, and measurement error is likely to confound attempts to understand the actual nature of the spawner-recruit relationship, if one exists (Sissenwine and Shepard 1987). Despite the problems and limitations with describing and quantifying the relationship, it remains one of the most important areas of research by fisheries biologists and managers today, especially as most estimates of reference points for more complex models are dependent in part on understanding the nature of the spawner-recruit relationship.

1.2.3 Yield Per Recruit (Dynamic Pool Model) Reference Points

Yield per recruit model reference points such as F_{\max} and $F_{0.1}$ became extremely popular as a result of the groundbreaking synthesis of Beverton and Holt in 1957; a legacy which both of these authors later found lamentable given the suite of fisheries problems that ultimately resulted from misguided application of their work (Beverton 1998, Holt 1998). It was rapidly becoming apparent that fluctuations in recruitment and the problems associated with determining the appropriate age at first capture (to avoid growth overfishing) were essential to fisheries theory. The premise behind F_{\max} is quite simply to maximize the yield per recruit by harvesting a population at that point in time where the biomass of a particular cohort (or year class) is at its greatest. This is the point at which the cumulative cohort weight gain due to individual growth equals the losses to the cohort from natural mortality.

Figure 1.3 illustrates the point in a very general sense, using data from Gulf of Alaska Walleye pollock as an example (for this example the number of recruits was assumed to be 1000, the juvenile instantaneous mortality rate (M) was 0.5 and adult mortality rate was 0.3). As the number of pollock decreases with age, total biomass increases initially as a result of rapid individual growth, peaks at approximately age 5, and then declines as mortality begins to exceed growth and cohort biomass declines. If one were making a decision based solely on maximizing total yield, independent of any other concerns (either biological or economic), the logical thing to do would be to simply harvest all pollock at age 5, which could be approximated with an extremely high fishing mortality rate and assuming all fish are fully vulnerable to the fishing gear at age 5 (fully selected) but invulnerable until that point.

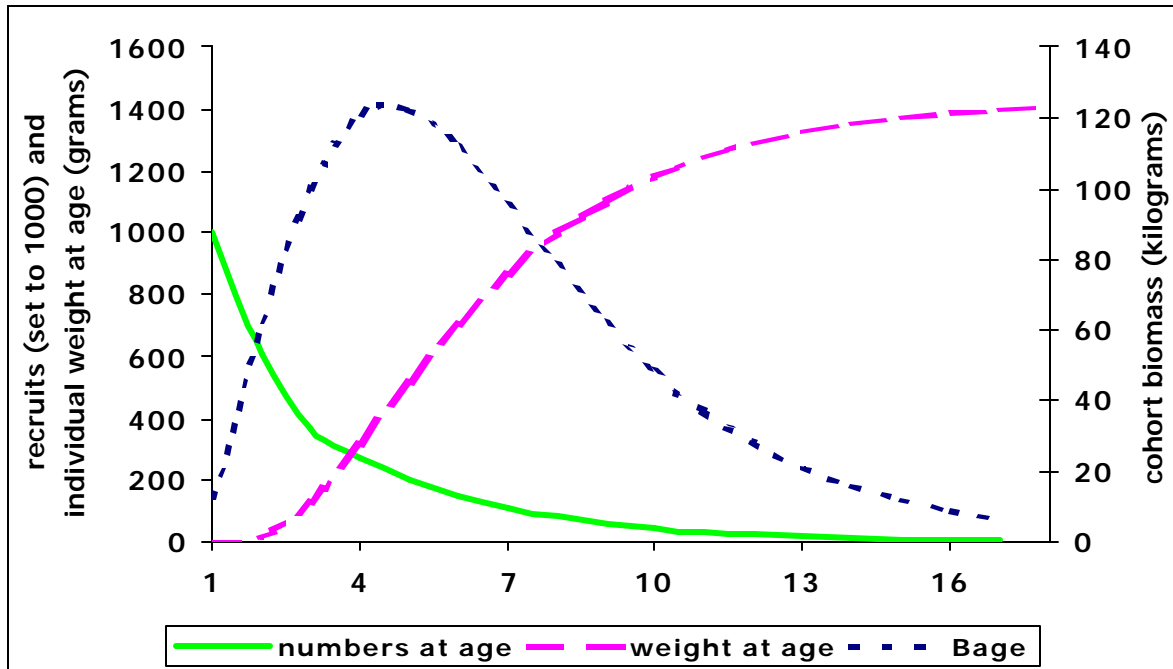


Figure 1.3: Numbers, weight at age and total biomass for an unfished cohort of Gulf of Alaska walleye pollock

In reality, what is really estimated by F_{max} is the optimal age (or size) for subjecting a year class to an optimal amount of fishing pressure that results in the maximum yield for a given selectivity (selectivity is the degree of availability or vulnerability of fish of a given size or age to fishing gear). Selectivity is key, for if the fish are targeted too early in their life, growth overfishing occurs (fish are harvested before the increase in cohort biomass with growth is matched by the decrease in total biomass with natural mortality), if they are targeted too late in life then potential yield may be forgone. However, in practice even this is quite difficult to achieve, as efforts to control selectivity generally include mesh size management controls or spatial management measures, which tend to be inconsistent over time, especially in cases of mixed stock fisheries. Additionally, there are often situations where larger fish are more desirable for economic reasons, for this reason Beverton and Holt (1957) included methods to estimate optimal fishing mortality based on alternative selectivity patterns; consequently an estimate of F_{max} for a given stock is not necessarily uniquely defined for any given fishery.

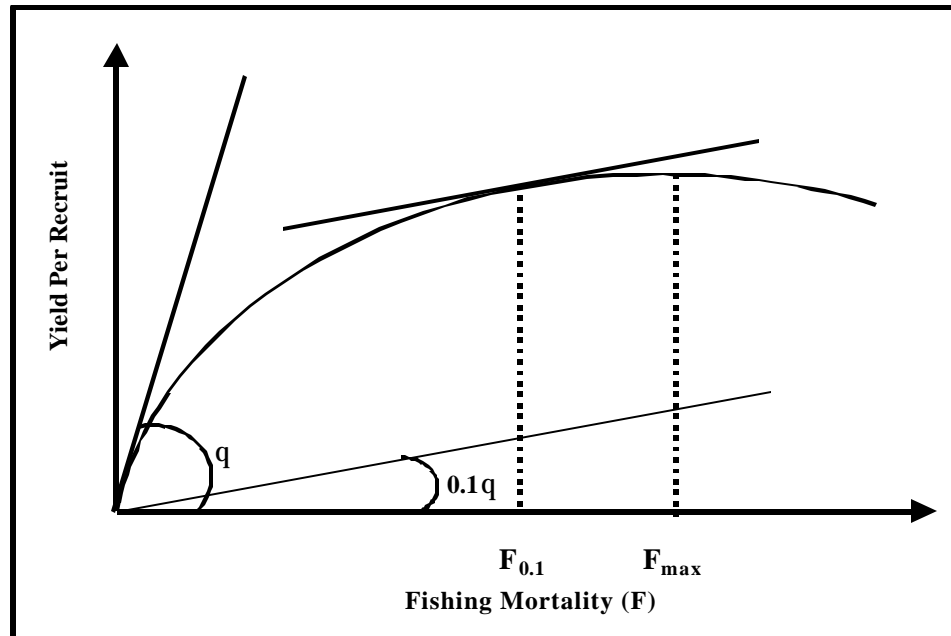


Figure 1.4: Relationship between F_{max} and $F_{0.1}$ on a typical yield per recruit curve. $F_{0.1}$ is the point on the curve where the slope of the tangent is equal to 1/10th of the slope of the line at the origin.

Gulland and Boerema (1973) noted that F_{max} as a fishing strategy does not incorporate the consequent survival of adult spawners to replenish the population, but rather assumes that the supply of new recruits to the population is constant. They argued that a more objective means of estimating a limit reference point for fishing that was more conservative than F_{max} would be to consider the marginal yield, or increase in landings, resulting from an additional unit of effort. They suggested that when the marginal yield (the additional yield gained with an additional unit of effort) equaled an (arbitrary) 10% of the original catch per unit effort in a fishery that it would be undesirable to increase fishing effort from a practical perspective; the return in fish caught was minimal relative to the effort exerted at this point in the curve. This strategy was described as $F_{0.1}$ in reference to the point on either the surplus production curve or the yield per recruit curve where the slope of the curve is 10% of the slope at the origin. Figure 1.4 shows the relationship of F_{max} to $F_{0.1}$ for a hypothetical yield per recruit curve (redrawn from Caddy and Mahon 1995), where it can be seen that while $F_{0.1}$ is a considerably lower fishing mortality rate than F_{max} , the shape of the curve is rather flat near the middle and thus the resulting yield is only

slightly lower, such that a large reduction in fishing mortality leads to only a small reduction in catch.

Based on the recognition that F_{\max} resulted in severe reductions of spawning biomass and that relatively little yield was forgone by adopting an $F_{0.1}$ policy, this reference point gained popularity as an objective throughout world fisheries; especially in North Atlantic fisheries (Hilden 1993, Maguire and Mace 1993). For example the 1984 Report of the ICES Working Group on Stock Assessments (ICES 1984) reported that $F_{0.1}$ was a preferable reference point to F_{\max} as the latter “may not exist for some stocks.” Some management agencies adopted similar, yet more conservative reference points (albeit equally arbitrary). For example in South Africa, hake stocks were managed under a strategy of $F_{0.2}$ based on the recognition that this provides an additional buffer against overfishing (Geromont et al. 1999).⁴ Additionally, Deriso (1977) derived some means of assessing the spawner-recruit conditions under which $F_{0.1}$ was sustainable and a suitable proxy to F_{MSY} for fisheries in which some spawner-recruit information was available.

1.2.4 The Development of Spawning Biomass per Recruit Reference Points

While $F_{0.1}$ was an improvement from a population perspective to F_{\max} , with very minor reductions in total yield, neither of these reference points could explicitly avoid recruitment overfishing and were furthermore extremely difficult to implement by managers (Hilden 1993). Cushing (1973) and Garrod and Jones (1974) had earlier argued that there was a growing need for a functional relationship that would combine stock-recruit relationships with conventional yield-per-recruit data to assess the relationship between total yield and spawning stock. Shepard (1982) also suggested that “If spawning stock biomass is accepted as the most suitable measure of population size underlying the determination of recruitment, then biomass-per-recruit (BPR) acquires a special significance as the measure of survival which is most helpful in understanding the behavior of a population in steady state.” Beddington and Cooke (1983) had earlier evaluated the implications of recruitment variability on estimates of potential yield and suggested that an escapement level of 20% of the equilibrium spawning biomass be used as a limit beyond

⁴ After 1995 management procedures for South African fisheries changed and alternative rates such as $F_{0.15}$ and $F_{0.075}$ were considered for various fisheries.

which lower recruitment declines should be expected; they also assessed the extent to which F_{\max} and $F_{0.1}$ policies would drive spawning biomass below this level and estimated the reductions in fishing mortality that would be necessary to avoid this. These early efforts opened the door to a new suite of reference points based on sustaining a viable fraction of the presumed values of either recruitment or of spawning stock prior to exploitation.

The stock assessment group for ICES (1984) was amongst the first to explore methods of examining spawning biomass per recruit data in relation to yield per recruit analysis, and came up with a sequence of reference points based on spawner-recruit relationships which they defined as F_{high} , F_{med} and F_{low} . These reference points are quite simply linear relationships that pass through the origin bracketing spawner-recruit data, such that F_{high} corresponds to the upper 90th percentile of observed recruits per unit of spawning stock (in other words recruitment might be expected to be above this line for a given unit of spawning biomass an average of 1 year in 10). Similarly, F_{med} corresponds to the 50th percentile (or the mean recruitment per spawning stock units) and thus reduces spawning stock biomass per recruit to the median observed in a set of spawner-recruit data. F_{low} corresponds to the lower 10th percentile. In all of these scenarios, the reciprocal of the slope is equal to the spawning biomass per recruit, which in turn allows one to estimate the fishing mortality rate associated with each point based on the relationship between spawners per recruit and F . The working group suggested that F_{med} corresponded to a level of fishing mortality “at which one is reasonably happy that the stock can reproduce itself comfortably,” whereas fishing effort greater than F_{high} represented substantial threat of stock collapse. F_{low} represented a level of fishing mortality with a (presumably) very low risk of stock collapse.

Shortly after the ICES Report, Sissenwine and Shepard (1987) followed up on their earlier work with a reference point denoted as F_{rep} , or the level of fishing mortality that would result in the replacement of spawning stock biomass over time; F_{med} is essentially an estimate of F_{rep} although Rosenberg et al. (1994) suggest that F_{rep} would forego potential yield in lightly exploited stocks and F_{med} could underestimate F_{rep} if the distribution of recruitment is highly skewed. In an unexploited stock, F_{rep} would be 0, which would correspond to no net change in stock biomass (excluding random variability or other trends), similarly for a heavily exploited stock F_{rep} would correspond to the fishing mortality rate that prevented further stock decline. Thus, in theory any

application of F_{rep} would be sustainable, as even at low biomass levels and yields the stock might not be expected to decline, regardless of whether the rate was higher or lower than F_{MSY} .

Sissenwine and Shepard argued that F_{rep} could thus represent a threshold, or limit, for depleted fisheries; a rate beyond which further stock declines were inevitable.

A more important breakthrough occurred when Gabriel et al. (1989) evaluated data for Georges Bank haddock and generated a set of spawning stock biomass per recruit (referred to as SPR, for Spawner Per Recruit)⁵ curves for alternative combinations of F and t_c (age at entry into a fishery). These were essentially very simple extensions of the dynamic pool models developed by Beverton Holt to estimate yield per recruit, except that they added maturity schedules and reproductive output to estimate the total spawning potential of a typical recruit or cohort over time. Reducing the expected spawning biomass per recruit is a strategy which considers how much the spawning potential of a typical recruit under fishing pressure is reduced relative to that which would exist with no fishing pressure. As a simple example, suppose an average female fish began spawning at age 5, spawned the same number of eggs (say 100) every year and suffered no mortality until it died at age 8. The average female would have produced 400 eggs over its lifetime. If the averaged fish from the same population was invulnerable to fishing until its 7th birthday, but all fish were immediately caught as they turned 7, then each female would have instead produced only 200 eggs, or 50% of their potential without a fishery. Such a strategy would be an $F_{50\%}$ strategy. While this example is simplistic, it is the conceptual basis for all Spawning Biomass Per Recruit (SPR) management strategies and reference points.

A key objective in the work of Gabriel et al. (1989) was to assess the levels of SPR necessary to maintain (prevent further declines) the haddock population, based on what was known about the spawner-recruit relationship. Their results indicated that the observed SPR level was 16% of the equilibrium (or unfished) SPR, and furthermore was too low to rebuild, or even replace, the stock at (then) current exploitation rates. They estimated that an SPR 30% of the maximum would be necessary to maintain stock replacement, and their results were then used to estimate the mesh

⁵ The terminology for SPR is now more or less standardized, but numerous terms exist in much of the early literature; many of these were summarized by Rosenberg et al. (1994) as being essentially synonymous with spawner per recruit, such as spawning potential ratio, percent spawning stock biomass per recruit (%SSB/R), percent maximum spawning potential (%MSP) and percent eggs per recruit (%EPR). Additionally, the authors noted that these concepts were actually applied to numerous fisheries under the jurisdiction of the New England Fishery Management Council (NEFMC) several years before Gabriel et al. (1989) paper was published.

size for trawl gear (the primary regulatory measure for New England groundfish during that period) that would lead to a replacement level of 30% of the equilibrium SPR. Similar results for other New England species suggested conservation targets for SPR of no less than 20% for cod, 25-30% for yellowtail and 20% for other species (Anon. 1987, as cited in Goodyear 1993). Their work immediately preceded regulations in 1989 that required Fishery Management Councils to specify overfishing definitions for all stocks managed under federal FMPs, with a particular focus on the prevention of recruitment overfishing. Consequently, this work and that which immediately followed it resulted in SPR analysis becoming the theoretical and empirical basis for the vast majority of overfishing definitions in U.S. fishery management plans (Rosenberg et al. 1994). The common depiction of these results are as $F_{\%SPR}$, where $F_{40\%}$ represents the fishing mortality rate that results in 40% of the spawning potential per recruit for an unfished cohort, and $B_{40\%}$ is the corresponding biomass at that fishing mortality rate.

Clark (1991) simulated a large number of life history traits (growth, maturity, mortality and spawner-recruit relationships) considered to be ‘typical’ of mid-latitude groundfishes and explored fishing mortality rates that approximated the MSY for these stocks and the resulting levels of spawning stock biomass associated with these rates.⁶ Clark found that while the yield relative to fishing mortality was highly dependent upon the form of the spawner-recruit curve (in other words, on the extent of compensatory behavior in any given spawner-recruit relationship), the yield plotted against relative spawning stock biomass (SSB) was very similar for all curves. Yields were consistently very close to MSY when the spawning biomass was fished down to between 35 to 40% of the equilibrium biomass, consequently a fishing strategy that would accomplish this would result in yields approximating MSY for most fisheries. In the absence of information regarding equilibrium biomass, Clark also suggested that an alternative harvest rate strategy of reducing spawning biomass per recruit (SPR) to a point near the middle of the 20 to 60% range would maximize the minimum yield among all of the spawner-recruit relationships considered; a value he referred to as the “maximin yield”, or F_{mmy} . This strategy was essentially the same as that taken by Gabriel et al. (1989), and is more appropriate if unfished biomass estimates are unavailable or if stocks fluctuate substantially over longer time scales. Clark estimated that this strategy generally resulted in yields of at least 75% of MSY for extreme

⁶ He based this approach on that performed earlier by Lenarz (1984) who had plotted potential spawner-recruit relationships along with growth and maturity information for the then newly developed and very heavily exploited widow rockfish stocks (*Sebastes entomelas*) off of California, Oregon and Washington.

(highly compensatory) S-R curves and 90% or more of MSY for more intermediate S-R curves, although this strategy was considered less robust and more sensitive to errors than the strategy of reducing spawning biomass.

Clark closed his discussion with a caution specific to many stocks in the North Pacific, which had already exhibited large-scale changes in abundance under low fishing pressure. He suggested that for such highly variable stocks, attempting to maintain a consistent biomass would not be practical, but rather his second strategy (based on SPR) would allow the fishery to track the yield curve through large changes in abundance, resulting in yields close to MSY under varying recruitment or production regimes.⁷ Consequently, in a later paper (Clark 1993), he further evaluated the effects of variability on recruitment and determined that $F_{40\%}$ would reduce the risk of encountering lower spawning biomass levels (which he defined as less than 20% of the equilibrium biomass) in situations with highly variable recruitment, although even with this approach one would expect some stocks to be overfished and some stocks to be underutilized. When recruitment variability was autocorrelated (suggesting regime-like behavior, or essentially long-term trends of above or below average recruitment associated with climate or other physical conditions) he found that the risk of spawning biomass declining below 20% during some periods increased for most spawner-recruit relationships. In a more recent paper, Clark (2002) also pointed out that in his original paper, the consequences of the $F_{35\%}$ or $F_{40\%}$ strategies to population biomass under low productivity scenarios were never reported, consequently for populations with poor productivity (such as many west coast rockfish species) the application of these harvest rates would often result in very low biomass levels, that would qualify as overfished by current U.S. standards.

Goodyear (1993) also conducted simulations with SPR models based on his earlier work with potential fecundity per recruit (Goodyear 1977) and arrived at conclusions similar to Clark's, adding that a key attribute of the SPR approach was that fractions of spawning potential could be

⁷ Ultimately, managers agreed with the conclusion that Clark's first method (the strictly biomass-based approach) was impractical, and indeed this strategy was never explicitly implemented in a management context (to the best of the author's knowledge). References to Clark's work are generally with respect to his alternative approach, which was itself really an independent manifestation of the SPR approaches derived by Gabriel (1989), Mace and Sissenwine (1993), Goodyear (1993), and others. Interestingly, the Eastern Bering Sea pollock stock was referred to by Clark as 'clearly a candidate for a biomass-based strategy', such that a target spawning biomass of four million metric tons, at the center of a range between two and six million metric tons, would provide the bulk of MSY regardless of the true form of the S-R relationship

apportioned between alternative harvest strategies associated with different fisheries that might have varied selectivity patterns or market objectives. Both authors concluded that either of the two strategies would be appropriate for determining target reference points for optimal harvest rates that would approximate MSY in the absence of more stock-specific estimates and where the nature of the stock-recruit relationship (and consequently the degree of compensation in any given stock) was unknown. One problem in implementing this approach is that because the nature of the stock-recruit relationship is unknown, the number of average recruits in the unfished state, and consequently the unfished biomass, is unknown. Most current assessments use recruitments averaged over a given time period as a proxy for equilibrium recruitment, but this of course assumes that recent recruitments represent the long-term average, and consequently may underestimate unfished biomass levels (B_0) if historical depletion has resulted in decreased recruitment or if climate or other factors have resulted in unfavorable recruitment regimes. Despite this problem, the spawner per recruit (SPR, or $F_{\%SPR}$) approach was quickly adopted by Councils throughout the United States (and to a lesser extent, in some Canadian fisheries) and has continued to be the cornerstone of most fishery management plans (FMPs) in the U.S. Figure 1.5 shows an example of one such SPR curve for Pacific hake (based on data from Hessler et al. 2002), in which the relative spawning biomass per recruit is estimated at alternative exploitation rates.

While Clark argued that these reference points were appropriate proxies for MSY for many fisheries, Thompson (1993), Mace and Sissenwine (1993), Goodyear (1993) and others had focused on using SPR analysis to better define limit, or threshold reference points to avoid overfishing and the risk of stock collapse. Thompson (1993) specifically examined the potential for overfishing under scenarios in which populations were maintained under multiple equilibria, consistent with regime-scale variability in either productivity or recruitment patterns (and similar to the autocorrelation in recruitment evaluated in Clark's 1993 paper). Thompson simulated stock-recruit relationships that allowed multiple equilibria and evaluated threshold reference points that would avoid overfishing and stock collapses under such conditions. His conclusions strongly suggested that stock collapses were highly unlikely as long as biomass levels were greater than 20% of the equilibrium biomass, and that target fishing mortality rates should be set to maintain spawning biomass per recruit at levels no less than 30% above the unfished levels (results similar to Beddington and Cooke 1983, Gabriel et al. 1989, Goodyear 1993 and others).

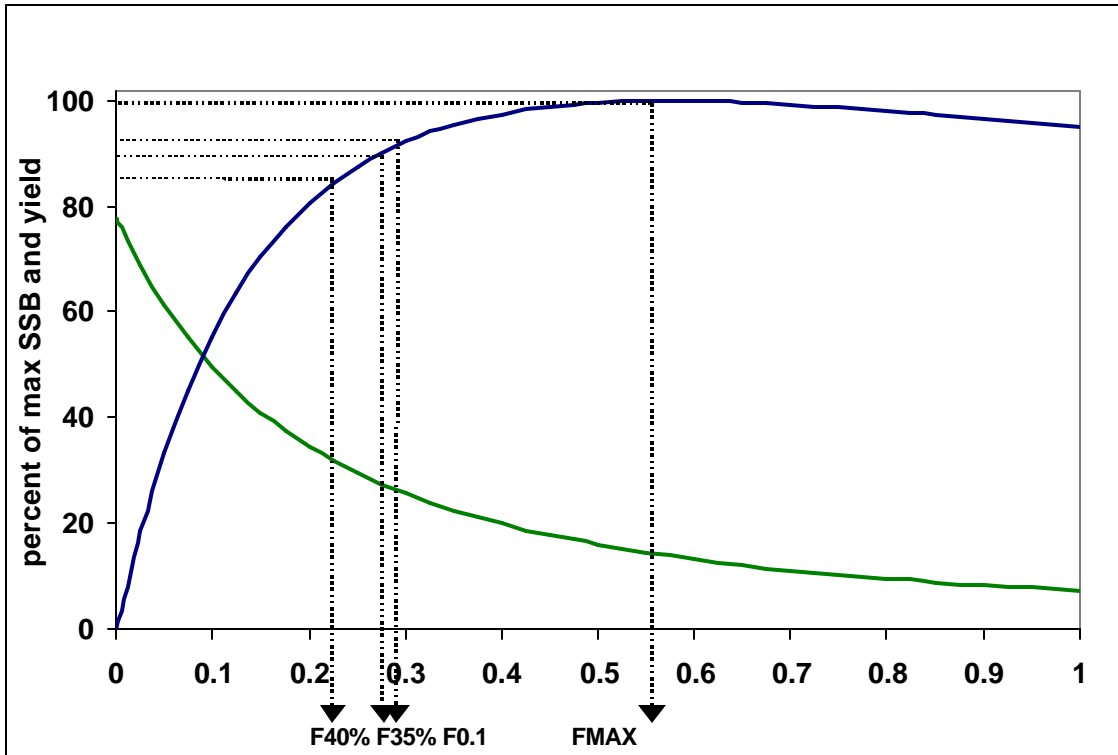


Figure 1.5: Relationship between relative spawner per recruit and relative yield per recruit for Pacific hake, based on data from Helser et al. (2002), illustrating the trade-offs between the reproductive output and yield under four alternative fishing strategies.

Under scenarios in which unfished biomass estimates were unavailable, he found that constraining F to less than 80% of M was also likely to be sufficient to avoid stock collapse. Furthermore, in his evaluation of stocks in the North Pacific for which estimates of unexploited biomass levels did exist, he found that thresholds set at 20% of the unfished biomass posed no significant constraints on the fishery.

1.2.5 Reference Points to Avoid Overfishing

Mace and Sissenwine (1993) defined F_{τ} as the ‘extinction threshold fishing mortality rate’, analytically defined as the slope of the spawner-recruit curve at the origin, which is quite simply the rate that would drive a stock to either commercial or ecological extinction if applied continuously (this is commonly referred to as both F_{crash} and $F_{\text{extinction}}$ as well). They suggested that F_{rep} was likely to be a conservative estimate of F_{τ} under stable environmental conditions

(albeit an overly conservative threshold for stocks close to their unfished equilibrium levels), and could actually be a more appropriate fishing target for stocks with moderate or strong compensation; although F_{rep} could also either over or under estimate F_{τ} if environmental conditions during the observation period had produced either high or low survival rates. They then sought to summarize data on replacement levels of %SPR and other referenced points to determine whether there was evidence for consistent effects of life history parameters or taxonomic groupings that might be useful in defining overfishing thresholds for species with inadequate data for quantifying such thresholds on a stock specific basis.

There results did indeed suggest strong differences; flatfish, Atlantic cod and some Atlantic herring appeared to have a higher resilience to fishing (low levels of replacement %SPR, which suggested a greater compensatory response by the population) while smaller gadoids and small pelagics having less resilience to fishing (higher levels of replacement %SPR suggesting less compensation). Levels of replacement %SPR for all cases examined had a mean of 18.7%; with Atlantic cod and flatfish having means of 6.8% and 14.5% respectively, and other gadoids and other clupeids having means of 25.7% and 37.5% respectively. Interestingly, their results suggested that many stocks of smaller gadoids appeared to have relatively high levels of replacement SPR, including North Sea whiting (50%), Northwest Atlantic silver hake (42%) and Eastern Bering Sea Pollock (43.8%). The authors suggested that the gadoids that did seem to have higher replacement SPR values were those that reached relatively smaller maximum sizes and/or early maturation (associated with higher natural mortality rates); small pelagics similarly tended to have considerably higher replacement SPR values. Additionally, while the mean %SPR was close to 20%, they suggested that this would be a risky threshold for species that were poorly (or un) represented in their survey, and offered a preliminary threshold replacement %SPR of 30% (based on the 80th percentile of observations of the stocks they surveyed; this too would not be sufficient to conserve all stocks, but rather most stocks). Because this level was very similar to the $F_{35\%}$ 'target' recommended by Clark (1991) they in turn suggested that Clark's inferences might not be appropriate for some stocks, although they acknowledged that their threshold would likely be overly conservative for many others.

To more carefully evaluate the growing number of methods for deriving reference points meaningful for defining both targets and overfishing limits, a review panel was established to

assess the strengths and weaknesses of various approaches in U.S. fisheries (Rosenberg et al. 1994). Although considerations regarding a single, generic definition of overfishing had met with resistance by regional Councils, the Panel felt as a conceptual framework for defining overfishing, some definition was useful, and agreed that a stock would be considered recruitment overfished (absent convincing evidence to the contrary) if recruitment fell below half of the expected maximum (or equilibrium) level (F_{50R}). This at least framed overfishing in a common currency and allowed the Panel to evaluate whether alternative approaches seemed to accomplish this objective. The panel noted that of the overfishing definitions reviewed in their report, the vast majority (67%) were fishing mortality rate definitions,⁸ and the vast majority of these were based on a minimum spawner per recruit (SPR) analysis (half used 20% SPR, another third used 30% SPR). However the Panel also found was that many of the overfishing definitions called for the use of stock-specific information that was rarely available, resulting in the widespread use of substitute measures.

Mace (1994) pointed out both that the utility of any given reference point was dependent upon the user, that there were rarely sufficient data to make a sound judgment based simply on a reference point alone, and the same reference point might be categorized differently depending on both the stock and the assessment scientists or managers in question. She looked at estimates of F_{MSY} , $F=M$, $F_{0.1}$, F_{max} , $F_{20\%}$, $F_{35\%}$ and F_{τ} from simulated data, and evaluated their ability to achieve long-term yields close to MSY while avoiding overfishing. Mace defined τ (or tao) as the ratio between the slope corresponding to spawners per recruit at with no fishing mortality and the slope at the origin, as the parameter that determines the degree of compensation in the spawner/recruit relationship of a stock (as opposed to F_{τ} which Mace defined as the fishing mortality rate that would cause a stock collapse). She then evaluated the performance of each of these reference points under different scenarios of the life history parameters τ , K (a growth coefficient) and M (natural mortality). Among her general conclusions was that the validity of any of these fishing mortality rates or biomass levels as appropriate targets or thresholds were extremely dependent on life history characteristics. She concluded that a reference point of $F_{20\%}$ would be a useful threshold for stocks that are reasonably certain to have at least ‘average’ resilience, although a more prudent threshold would be $F_{30\%}$. Her default target fishing mortality

⁸ The remaining third of the definitions were biomass based; most of these were salmon stocks managed on constant escapement strategies that themselves were rooted to spawner-recruit relationships.

rate was $F_{40\%}$, which (like Clark) she found to be very similar to $F_{0.1}$ when recruitment and maturity schedules coincide. This value also approximated F_{MSY} for most values of τ , and importantly did not exceed F_τ except for very high values of τ (or very low compensation).

Myers et al. (1994) continued the search for defining thresholds for recruitment overfishing by compiling stock and recruitment data on 72 fish stocks which had at least 20 spawner-recruit data points and evaluating three types of threshold estimation methods to these datasets. The first method was the threshold SSB at which recruitment was reduced to $\frac{1}{2}$ the predicted maximum by a parametric stock-recruit model, or F_{50R} (essentially equivalent to F_{rep} of Sissenwine and Shepard 1987). The second type of methods were based on determining a level of stock size which would still be capable of producing a good year class when environmental conditions were favorable. Finally, the third type were methods based on defining the threshold as a fraction of the virgin, or unexploited spawning stock biomass, similar to the estimates compiled by Mace and Sissenwine (1993) and others. Their results suggested that the use of a percentage of SSB provided the most conservative estimates of spawning biomass at the threshold. Of the three S/R curves used, the Beverton-Holt was the most conservative in this scenario, followed by the Shepard and the Ricker. The methods based on 50% of the maximum recruitment using a standard S/R curve generally led to the most aggressive threshold (lowest SSB thresholds).

The authors concluded that for most of the stocks they assessed (which included a wide range of species but were dominated by cod, herring and salmon stocks), there exist biomass thresholds that could be used to avoid recruitment overfishing, and that methods based on estimating 50% R_{max} (F_{50R}) provide the most reliable estimated threshold levels overall based on the clarity of their theoretical basis. The authors did not recommend methods based on 20% of SSB them for general use as they often placed the critical point well beyond the range of observations, there were inaccuracies in estimating virgin biomass, and the inappropriateness of applying a 20% level universally given substantial variability in the degrees of compensation in recruitment and other life history processes.

As the evaluation of threshold and target reference points continues, the increasing use of large datasets to make general inferences about fish population dynamics has led to increasing insights

regarding both expected and unexpected population responses to fishing. For example Myers et al. (1995) specifically focused on the potential for compensatory population behavior in fish populations. Compensation (also be referred to as the allee effect, or inverse density dependence) is essentially the inverse of compensation; compensatory behavior occurs when populations experience reduced rates of survival and per capita reproductive success at low population levels.⁹ Of 128 heavily exploited stocks examined by Myers et al., they found some evidence for compensatory behavior in only three, results hailed as highly significant to fisheries managers, as they suggested greater resilience of stocks to overfishing; even severely overexploited stocks could be expected to recover once fishing mortality was reduced or eliminated. Liermann and Hilborn (1997) followed up on this work, and although they reached similar conclusions, they cautioned that many models that did not include compensation fit the data only slightly better than the models that did, and consequently the potential for compensatory behavior should not be excluded.

Another of the more significant findings from meta-analytic techniques was that of Myers et al. (1999) in which over 700 spawner-recruit relationships were evaluated to arrive at maximum annual reproductive rates for fishes (the slope at the origin of spawner-recruit relationships, or the rate at which spawners can produce replacement spawners at low population sizes; also akin to the maximum population growth rate 'r' at low stock sizes in a surplus production model). The authors determined that this value typically ranges between 1 and 7, and tends to be similar for different stocks of the same species. Amongst the significance of this finding was the authors repudiation of lingering assertions that recruitment is independent of spawning biomass, and the recognition that this information could be used with species specific maturity and fishing mortality schedules to derive an absolute biological limit of fishing; for as the age of selection to the fishery decreases, the limiting fishing mortality drops very quickly. Myers and Mertz (1998) suggested similarly that if selectivity patterns are such that an individual fish can spawn at least once before being fully vulnerable to a fishery, then it could be (theoretically) impossible to fully collapse a stock even if fishing mortality targets are exceeded. The inverse of this logic is that

⁹ Mechanisms for such behavior are varied, but could include increased effort required to find mates or increased vulnerability to predators resulting from an inability to perform group defense strategies. For example Levitan et al. (1992) found that the spawning efficiency of red sea urchins (*Strongylocentrotus franciscanus*), which are broadcast spawners (have external reproduction), may decline substantially more than the relative declines in total density. Liermann and Hilborn (2001) discuss both the mechanisms and the implications of compensatory behavior in a wide range of populations within the context of extinction risk, fisheries management and pest control.

stock collapses are expected for some species, particularly bycatch species, with late maturity, and one example they cite was the extirpation of the “common” skate (*Raia batis*) from the Irish sea, which resulted from a combination of large hatch sizes (meaning that even age 0 skates were vulnerable to most fishing gear) and late (age 11) age at maturity. The recent collapse of the barndoor skate in the Northwest Atlantic may be another example of a similar scenario (Casey and Myers 1998).

There is also emerging reason to believe that the potential for depensation in marine fish populations at low abundance levels is real. Hutchings (2000a and 2001) revisited the meta-analysis data from earlier studies to assess the number of observed recoveries from previous prolonged declines in fished populations. In contrast to the widely held belief that marine fishes are highly resilient to intensive fishing mortality, Hutchings found that as many as 40% of the stocks for which information was available showed little or no signs of recovery even 15 years after their original decline. His results suggested that clupeids, which tend to be more sensitive to long term environmental forcing, had the greatest tendency to recover while gadids, scorpaenids and other groundfish families were more likely to fail to show signs of recovery. Although it is not clear from these papers whether the role (or lack) of effective management was behind some of the declines, the results are suggestive that some populations may indeed be vulnerable to being fished beyond thresholds that prevent or hinder their recovery.

Consequently, Mace (2001) suggests that the use of biological reference points as indicators (or thresholds) for overfishing has met with far greater success than their application of targets, largely because the consequences of overfishing can be readily portrayed and appreciated in terms of both the resource and the fishery that depends upon it. While many studies have suggested that the risk of most individual populations to extinction is effectively quite low, both observations and model inferences suggest that these risks of collapse and consequent failures to recovery are both real and considerable.

2 Comparisons and Alternatives to Reference Points

From the start, nearly all efforts to derive new or unique reference points have been accompanied by comparative analysis of how they contrasted to either MSY or other reference points with regard to fishing mortality rates, yields, biological significance and real or perceived risks of stock collapse. All new reference points are essentially alternatives to those that preceded them, and there does appear to have been a trend over time towards both target and limit reference points that have generally been more conservative with respect to exploitation levels. Some examples of plausible and applied strategies to replace or supplement commonly applied reference points are also reviewed.

2.1 Comparative Evaluation: How Do Alternative Reference Points Measure Up?

Some comparisons between reference points are quite simple; as discussed earlier, $F_{0.1}$ was specifically derived to be more conservative than F_{max} yet result in similar yields; by definition it will always be less than F_{max} . Additionally, in any application of spawner per recruit (SPR) analysis where all else is equal, higher levels of SPR are associated with higher biomass levels, lower harvest rates and consequently reduced landings (in other words $F_{50\%}$ is a lower, or less aggressive, harvest rate than $F_{40\%}$). Yet the relative fishing mortality rates between most reference points vary tremendously as a result of a wide range of factors, including their role in food webs, their growth and maturity schedules and perhaps most importantly their selectivity to the fishery (which can usually be adjusted by management measures).

For example Deriso (1987) demonstrated that F_{max} was considerably more aggressive than F_{MSY} for most stocks and that $F_{0.1}$ was less than F_{MSY} for stocks with more compensation and greater than F_{MSY} for less compensatory stocks. He also found that setting F close to M was not a bad approximation of $F_{0.1}$ for stocks within a relatively broad range of life history parameters. When the predecessors to SPR based reference points (F_{high} , F_{med} and F_{low}) were developed by ICES (1994), they were compared with the more commonly applied reference points of F_{max} and $F_{0.1}$ for four ICES managed stocks with good stock-recruitment data. They were generally considered to be more appropriate as limits than targets; while F_{low} was found to be below $F_{0.1}$ in all cases

and below F_{\max} in three of four cases; F_{med} was above F_{\max} in all cases (and thus well above $F_{0.1}$) and F_{high} was more than double F_{\max} in all cases (ICES 1984).

Clark (1991) showed that $F_{35\%}$ and $F_{0.1}$ are generally very similar when recruitment and maturity schedules coincide, but $F_{35\%}$ generally exceeded $F_{0.1}$ when fish mature earlier than they recruit to the fishery, and was lower than $F_{0.1}$ when fish mature later than they recruit.¹⁰ A simple schematic of relative reference points is shown as figure 2.1(a), based primarily on these results and those of Mace (1994) for a ‘typical’ groundfish stocks with coinciding recruitment and maturity schedules. However note that *any* individual stock is likely to deviate from this generalization substantially. This is especially important with regard to developing fisheries on non-traditional species; the ‘typical’ groundfish life history characteristics (say, of a hake or cod with a natural mortality rate of 0.2 and where maturity and vulnerability schedules coincide) can be expected to vary substantially from those of species with more complex (or simply different) life histories. To emphasize this point, figures 2.1(b), 2.1(c) and 2.1(d) show several atypical examples drawn from Punt (2000) who reported a suite of biological reference points for six intensively fished southern hemisphere species.

Punt (2000) had modeled several species with a range of life history types and evaluated estimates of seven alternative reference points for each. He found that for some long-lived, slow growing species with low productivity, F_{MSY} , $F_{40\%}$ and $F_{0.1}$ strategies led to fishing mortality rates very close to F_{crash} , and in fact F_{\max} was often greater than F_{crash} while $F_{40\%}$ and $F_{0.1}$ could be greater than F_{crash} under estimates of extremely low productivity. The age structured models he used to estimate these reference points allowed for the possibility of a depensatory relationship, and among his conclusions were that there were likely to be biomass levels at which some populations (particularly elasmobranches, but potentially others) would be too small to sustain themselves, even in the absence of a fishery. These results, and the corresponding images tell us that the relationship of $F_{40\%}$ to F_{MSY} , F_{\max} , $F_{0.1}$, F_{crash} or any other reference points is rarely constant; in the example of hake, $F_{40\%}$ is very close to both F_{MSY} and $F_{0.1}$, but in the case of grenadier $F_{40\%}$ is less than half of F_{MSY} , and even $F_{30\%}$ is barely 2/3rds of F_{MSY} (although it is greater than $F_{0.1}$). For the School shark the reverse is suggested, with $F_{40\%}$ being almost three

¹⁰ To ensure this is clear; when it is said that $F_{35\%}$ ‘exceeds’ $F_{0.1}$, it implies that $F_{35\%}$ is a higher value of F , or a greater annual harvest rate which would be expected to generate higher yields and result in lower biomass levels.

Figure 2.1a: Imaginary stock with “typical” maturity and selectivity

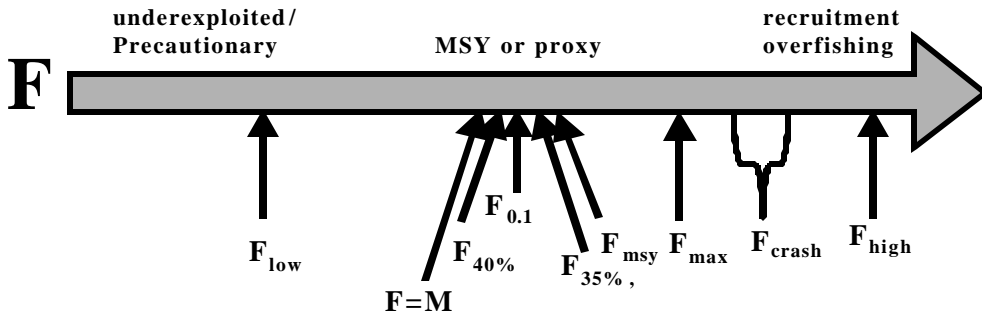


Figure 2.1b: Cape Hake

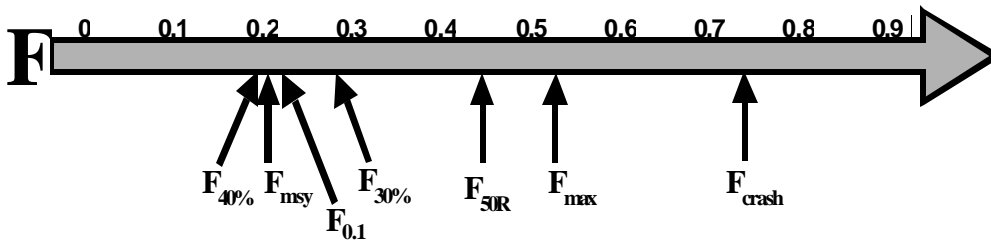


Figure 2.1c: Blue Grenadier

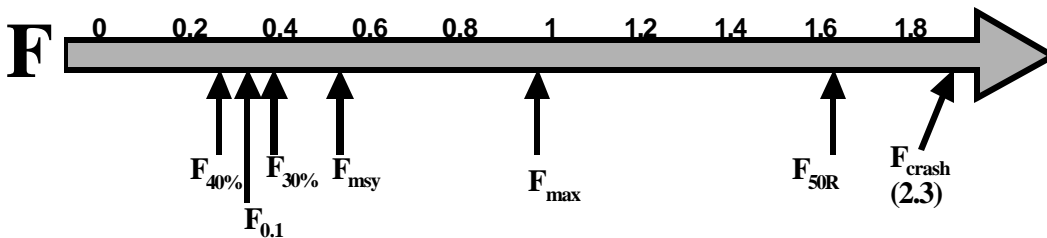
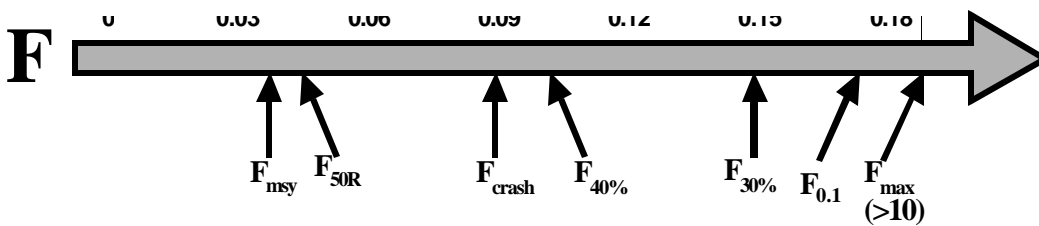


Figure 2.1d: School Shark (poor compensation scenario)



times the value of F_{MSY} , but more importantly $F_{30\%}$, $F_{40\%}$, $F_{0.1}$ and F_{max} were all slightly to substantially higher than F_{crash} ! Although this example was the least compensatory of three potential parameter sets for the School shark, and the other parameterizations suggested that $F_{40\%}$ (and other the points) were not less than F_{max} , the point was simply to illustrate that the wide range of plausible life histories leads to an inability to consistently predict which of a suite of reference points might be more conservative than others.

As stated earlier, one of the most often cited references for the application of $F_{35\%}$ and $F_{40\%}$ as proxies for F_{MSY} came from the work of Clark (1991) who used simulated data to conduct his comparisons, focusing on a range of life history characteristics typical of temperate water shelf species of the North Atlantic and North Pacific and a range of spawner-recruit curves. His results suggested that for a broad range of spawner-recruit curves and life history parameters, but those in which maturity and recruitment to the fishery schedules coincided, $F_{35\%}$ was slightly less than (but over 90% of) F_{MSY} , was difficult to distinguish from $F_{0.1}$ and was slightly higher than $F=M$ (which tended to correspond to approximately $F_{42\%}$). By contrast, $F_{35\%}$ generally exceeded $F_{0.1}$ when fish mature earlier than selected to the fishery and was lower than $F_{0.1}$ when fish mature later than they recruit. Mace and Sissenwine (1991) also found that $F_{0.1}$ tended to lie between $F_{35\%}$ and $F_{40\%}$ (an average of $F_{38\%}$) for most of the taxonomic groups they compiled statistics for, while F_{max} tended to lie between $F_{15\%}$ and $F_{25\%}$. For stocks with a low natural mortality rate, Mace (1994) also found that $F=M$ is not likely to be a conservative strategy.

Thompson (1993) compared target harvest strategies and fishing mortality rates derived from various methods from approximately 20 stocks from the Northeast Pacific with F_{MSY} , $F_{30\%}$ and $F=0.8M$. With the exception of sablefish, $F_{0.1}$ was generally very close to F_{MSY} for most stocks and $F_{30\%}$ tended to be more aggressive than either of these, with $F=0.8M$ generally being more conservative. Yet despite these generalities, Thompson found that none of the potential harvest rates were consistently conservative with respect to the others, instead any of these alternative strategies could have led to significantly greater exploitation rates than other strategies for some species. For example, his results suggested that the harvest rate for Bering Sea pollock under an $F_{0.1}$ strategy would be the same as under an F_{MSY} strategy (0.31), both of which were a sliver higher than $F=M$ (0.3) but substantially lower than $F_{30\%}$ (0.49). For Pacific cod F_{MSY} was 0.18, $F_{30\%}$ was 0.31 and $F=M$ was approximately 0.29, and for sablefish, $F_{0.1}$ was 0.13, whereas F_{MSY}

was estimated at 0.27, $F_{30\%}$ was 0.18 and $F=M$ was 0.1. In other words, $F_{30\%}$ was much higher than F_{MSY} for pollock and cod, but lower for sablefish. Similarly, $F=M$ was roughly equal to F_{MSY} for pollock, was less than half F_{MSY} for sablefish but slightly greater than F_{MSY} for Pacific cod. While estimates of these reference points have likely changed in the decade since this comparison was reported, the examples further serve the purpose of illustrating the extent to which comparisons of reference points are dependent upon the life history characteristics of the species in question.

As discussed earlier, Mace (1994) compared threshold reference points under a range of life history (growth and maturity) parameters with alternate levels of compensation in spawner recruit curves (as estimated by the parameter τ). Her analysis suggested that F_{MSY} and F_τ both decrease with increasing τ (less compensation in spawner-recruit relationships) and increase with K (a growth coefficient) and M (natural mortality rate). Both of these reference points have the greatest sensitivity to τ , then to M and lastly to K . For stocks with low values of τ (highly compensatory) F_{MSY} was usually well below F_τ ; suggesting low risk of stock collapse at F_{MSY} . The fishing mortality rates estimated by $F_{0.1}$, F_{max} , $F_{20\%}$, and $F_{35\%}$ were not influenced by τ , but all increased with both M and K . In different parameter combinations of M and K , $F=M$, $F_{0.1}$ and $F_{35\%}$ were generally very similar, although $F_{35\%}$ was usually slightly higher than $F_{0.1}$. F_{max} was not always definable; when it was it was generally close to the $F_{20\%}$ level. In terms of S/R relationships, Mace found that F_{MSY} was always higher using a Ricker stock-recruit relationship as opposed to a Beverton-Holt, the reason being that the Ricker spawner-recruit relationship has a greater potential for high compensation at median stock sizes.

Collie and Gliesson (2001) are among those authors whom have compared existing single-species reference points with regards to their application in a multispecies context; they used the Baltic Sea fish community as an example of attempting to estimate “bottom-up” consequences of fishing at lower trophic levels. Their basic conclusion was that reference points such as F_{MSY} , $F_{0.1}$, and $F_{40\%}$ were generally robust for higher trophic level predators (such as Baltic sea cod) in which natural mortality and other biological parameters remained relatively stationary over time, but were inappropriate for forage species (such as Baltic Sea sprat) which had predation-dependent natural mortality rates that fluctuated substantially. Their results suggested that reference points which increase as M increases (which are most ‘per recruit’ types of reference

points, such as $F_{40\%}$, $F_{0.1}$, F_{\max}) are inappropriate for forage species, although they suggested that alternatives such as F_{MSY} and F_{med} could be sustainable for some forage species under all but the highest predation mortality. A more appropriate alternative was to maintain constant total mortality by decreasing F when natural mortality increased, although the challenges associated with estimating changes in M were not explicitly addressed in their work. However these inferences have led to the harvest rates for many forage species being set lower than would be justified by many reference points, Maguire and Mace (1993) cite one such example for capelin in the Northwest Atlantic.

In general, the work by Clark (1993), Mace (1994) and many others since suggested that $F_{40\%}$ as a proxy for F_{MSY} and a strategy for highest long-term average yield can generally be considered “safe” in the context of avoiding recruitment overfishing, as it usually falls well below F_{τ} for the vast majority of stocks and their corresponding life history strategies. Both authors cautioned that the application of any targets or thresholds should be dependent upon both the degree of compensatory behavior in a given stock and other life history parameters. The varied comparisons of alternative reference points for various stocks, both real and simulated, illustrate all too clearly that alternative reference points will measure up very differently to each other depending upon the characteristics of the stock, and most importantly the nature of the spawner-recruit relationship, which is rarely well known.

One final message is that there are often wide ranges of biomass or spawning biomass per recruit associated with very small changes in fishing mortality rates and total yields. The development of $F_{0.1}$ as a harvest strategy was predicated on the observation that it led to only slightly reduced landings to those under an F_{\max} strategy, with a consequently substantially greater average biomass. Two additional examples are worth presenting here, the first (figure 2.2) is derived from a simple surplus production (Shaefer) model at equilibrium (from Caddy and Mahon, 1995) and simply shows expectant yields (as a percentage of MSY) resulting from alternative fishing rates (also shown as a percentage of F_{MSY}). The resulting declines in yields are minor; for example a ten percent reduction in F from F_{MSY} results in only a 1% loss in yield, and a 20% reduction ($F=0.8 F_{\text{MSY}}$) results in only a 4% loss in yield. The second example is from Restrepo et al. (1999) where the modeling approach of Mace (1994) was replicated to compare the consequences of fishing at both F_{MSY} and $0.75 F_{\text{MSY}}$. Using the same range of parameter values

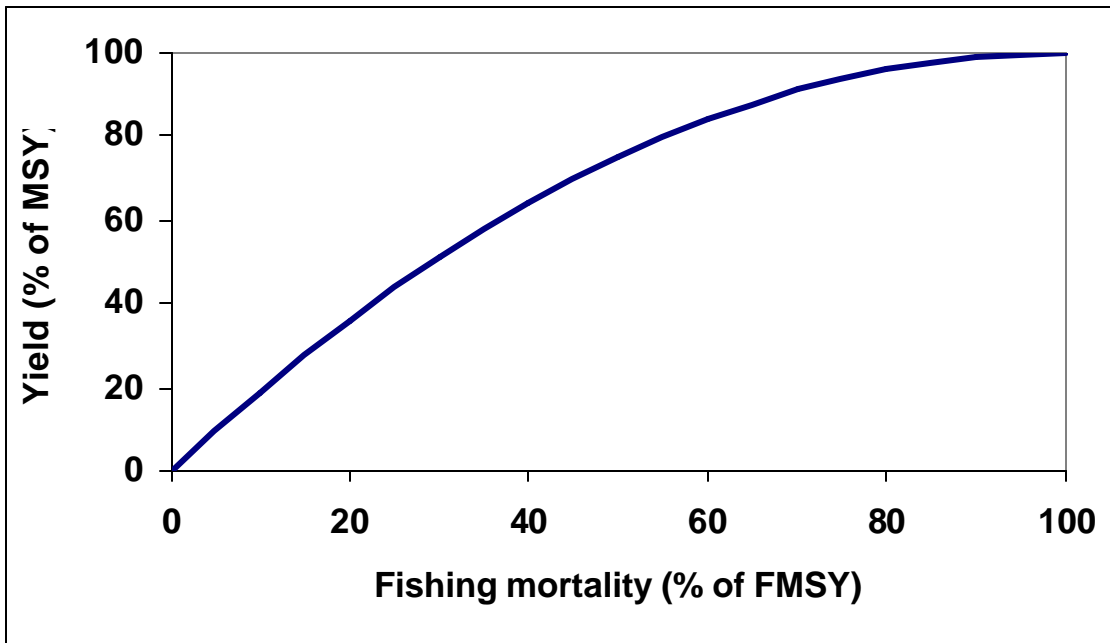


Figure 2.2: Percentage change in yield with corresponding percentage change in fishing mortality rates (based on Caddy and Mahon 1995).

as Mace (1994), it was shown that fishing at $0.75 F_{MSY}$ resulted in an extremely minor reduction in total yield (between 95 and 98% of the yield at F_{MSY}) with a substantially greater level of biomass (between 127 and 131% of the biomass at B_{MSY}).¹¹ These results clearly demonstrate that significant increases in average biomass levels of heavily exploited populations are possible with only minor reductions in yield. Thus it should be expected that a precautionary approach should generally result in mean biomass levels that tend to remain noticeably higher than 40% of their equilibrium spawning biomass levels ($B_{40\%}$), yet result in only slightly reduced yields over the long term.

2.2 What Are The Alternatives to Commonly Applied BRP's?

As summarized in Mace and Gabriel (1999), many international fisheries management bodies have continued to rely on MSY , F_{MSY} and their proxies as limit reference points, with precautionary buffers applied to these points in arriving at target harvest rates. The suite of

¹¹ These results were for the runs performed with a Beverton-Holt spawner-recruit relationship; use of a Ricker S/R curve generally suggested slightly lower yields (94-98% of those at F_{msy}) and biomass levels (125-128% B_{msy})

reference points based on spawner per recruit (SPR) analysis (eg $F_{\%SPR}$) are for now the most commonly applied proxies for U.S. fisheries, particularly those in the Northeast Pacific. Clark (2002) points out that while the $F_{40\%}$ strategy may now appear too high for many fisheries, harvest rates based on alternative targets may still be desirable. Clark's reanalysis of alternative levels of compensatory production suggested that adoption of strategies of $F_{50\%}$ and $F_{60\%}$ would be more reasonable for low productivity stocks (stocks with low compensation), and result in relatively minor forgone harvests for stocks of average or above average productivity (10-15% with $F_{50\%}$ and 20-30% with $F_{60\%}$). Indeed, over recent year more conservative applications ($F_{45\%}$, $F_{50\%}$, $F_{75\%}$) have increasingly begun to be applied in many fisheries, and as these rates are usually used to estimate allowed biological catches (ABC's) that are themselves reduced by buffers as a precautionary measure effective fishing rates should be lower still. Additionally, a new generation of management measures is being developed and applied, generally in recognition of the shortcomings of managing fisheries based on data-poor inferences of sustainable harvest rates alone. These include the use of constant harvest rates (often with cutoff biomass levels), marine reserves and/or rolling closed areas and others, a few examples will be discussed here.

A growing number of west coast fisheries are now managed based on SPR targets or limits considerably lower than $F_{40\%}$. Concerns over widespread declines in Pacific coast rockfish stocks (*Sebastes and Sebastolobus spp.*) raised by Ralston (1998) and others suggested that the applied F_{MSY} proxies of $F_{40\%}$ might not be appropriate for long-lived and slow growing species. At a workshop focused on harvest rates for slow growing west coast species, Dorn (2002) used a hierarchical Bayesian model to jointly estimate stock-recruit (S/R) relationships of *Sebastes* rockfish stocks in the NE Pacific. He found that the SPR rates at MSY^{12} for most *Sebastes* stocks were clustered largely between $F_{40\%}$ and $F_{60\%}$ depending upon the S/R model and the model for recruitment variability; however West Coast Pacific Ocean Perch (POP) and Canary rockfish would likely produce their maximum yield at harvest rate below $F_{70\%}$. Basing his model

¹² The steepness of the spawner-recruit curve was the parameter of interest in this meta-analysis, which was in turn used to estimate F_{msy} . His hierarchical model suggested an overall average steepness of approximately 0.65 for *Sebastes* stocks (meaning that the stock would average 65% of equilibrium recruitment at a biomass of 20% of the equilibrium biomass), yet he noted that several stocks showed very low steepness (very poor compensatory response) such as west coast Pacific Ocean Perch and Canary rockfish. Furthermore, most stocks had very flat posterior distributions; indicating that the data is not very informative and a wide range of steepness values would fit the data.

based on west coast stocks only, Dorn found that most SPR harvest rates varied from $F_{45\%}$ to $F_{56\%}$, and suggested $F_{50\%}$ as a reasonably risk-neutral proxy of F_{MSY} for west coast groundfish; noting that a truly risk adverse strategy would justify $F_{55\%}$ to $F_{60\%}$ harvest rates. Finally, Dorn noted that the current Canadian policy for Goose Island POP stock was an $F=M$ policy, which corresponded to roughly an $F_{49\%}$ harvest rate; this too was considered by Dorn to be a fairly risk adverse strategy which resulted in a minimal (less than 5%) loss of potential maximum long-term yield. Dorn's analysis, and other work presented at that workshop, was used to justify the adoption of a 'risk-neutral' harvest rate of $F_{50\%}$ for rockfish species on the west coast; as well as to lower the harvest rate for sablefish and lingcod to $F_{45\%}$. Harvest rates for hake and flatfish remained at $F_{40\%}$ as a result of the observation that these species tended to be more resilient.

Another example of a more conservative application of %SPR based approach is the fishery for Antarctic krill, where an ad-hoc approach of $F_{75\%}$ has been implemented as a limit reference point. The Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR) was established in 1982, as a result of concern for growing fisheries on krill and the recognition that so many other Antarctic species had been overexploited in the past (Constable et al. 2000). The conservation principles upon which the Convention is based include 'standard' single-species approaches (that harvested stocks should not be allowed to decrease to the point where recruitment is threatened, and should be maintained at a level which produces the "greatest net annual increment") as well as ecosystem considerations, particularly with regard to higher trophic levels. The Convention states that ecological relationships between harvested species those dependent on them for prey or related in some other way must be maintained, and depleted stocks of any species should be recovered to the level mentioned in the first principle to assure this (additionally, fishing-related changes in the marine ecosystem which cannot be reversed in a period of 20 to 30 years should be prevented). Thus, their precautionary quota for krill is set at halfway between what the krill population itself could be expected to sustain within a single species context (using $F_{50\%}$) and no fishing for krill at all (Parkes 1999). This allows a fishery for krill at rates as high as $F_{75\%}$, thus leaving most krill production for the needs of predators in the system, rather than assuming all surplus production is safely removable by fisheries for human use. This approach is highly consistent with the observation that low trophic level forage species (or forage species with high natural mortality rates) are less resilient to intensive fishing mortality than higher trophic levels (Collie and Gliesson 1999), and thus merit more precaution.

Hilborn (2002) suggests an alternative to more precautionary harvest rates, arguing that even severely depleted populations can support sustainable landings, and that overfishing is less serious a problem than many of the socioeconomic problems faced by fisheries managers (such as overcapacity, poor profitability and regulation-induced discarding). He offers examples of fisheries for rock lobster and snapper in New Zealand, for which stock assessments suggest that current biomass levels have averaged on the order of 10% of the unexploited levels over the past three decades. In both of these fisheries (two of New Zealand's most valuable) catches have approximated those that would be anticipated at MSY; for example the snapper assessment estimated the biomass at $\frac{1}{2}$ the level that would produce MSY, but the stock is still able to sustain landings of 92% of MSY while (slowly) rebuilding. Hilborn suggested that this stock is being 'sustainably overfished', and that as a result the long-term rebuilding strategies implemented jointly by government and industry have avoided short term economic hardships to the industry. The SPR replacement levels estimated by Mace (1994) and the meta-analysis of populations conducted by Myers et al. (1999) support the idea that some stocks are capable of sustaining themselves at extremely low levels while producing yields close to the optimum, although such considerations exclude other potential ecological consequences.

Another class of harvest strategies has evolved to cope with species for which abundance and productivity appear to vary considerably in space and time in accordance with environmental conditions. These are fixed harvest rate strategies that include either (or both) a buffer of adult biomass as a form of insurance to maintain stocks during periods of unfavorable environmental conditions, and environmentally driven control rules that allow for greater harvest rates during periods of high productivity.¹³ Along the U.S. west coast these strategies have been implemented for highly dynamic coastal pelagic species such as Pacific sardine, northern anchovy and Pacific mackerel, all of which have varied tremendously in both abundance and productivity over the last century in response to both climate and fishing, trends comparable to other coastal pelagic fish stocks in upwelling ecosystems worldwide (Schwartzlose et al. 1999).

¹³ In a sense, this is only a slight adjustment to the fixed exploitation rate approach described by Walters and Parma (1996), who used model outputs to suggest that such strategies generally resulted in long-term performance within a few percentage points of the theoretical optimums for highly variable stocks with imperfect information.

Jacobson and MacCall (1995) demonstrated that a theoretical MSY for sardines under favorable environmental conditions could be greater than the total biomass of an unfished stock under unfavorable conditions, and concluded that a theoretical definition of maximum sustainable yield (MSY) as a constant level of catch should not be applied in fisheries for coastal pelagic species. Consequently, the current fisheries management plan (PFMC 1998) is based on the application of a baseline ‘cutoff’ population biomass, below which directed harvests are not allowed, and above which allowable landings are based on a constant fraction of the biomass above the cutoff. This approach was not necessarily original, it had been developed during the FMP for northern anchovy in the late 1970s, at which time there had been a great deal of debate regarding the significance of anchovies as forage both for other commercially important fishes (tunas, salmon and rockfish) as well seabirds such as the (then) ESA listed endangered Brown Pelican. The first northern anchovy FMP (approved in 1977) set quotas based on a percentage of the stock that was greater than 300,000 metric tons, although small amounts of landings for bait fisheries were allowed to continue at lower levels of abundance.

The Coastal Pelagics FMP adopted in 1998 was essentially an amendment to the original anchovy FMP, and the harvest strategy for sardines was similar, with an environmental twist. Instead of an allowable catch set at a fraction of the biomass above the cutoff level, the sardine fishery has an environmental control rule, which sets the harvest fraction between 5 and 15% of the population above the cutoff level depending upon the three year running average of sea surface temperatures (as measured from the Scripps pier in La Jolla, California).¹⁴ The key point is that this approach allows for high harvest rates during favorable environmental conditions but reduces fishing mortality substantially under unfavorable conditions and rapidly forces fishing mortality to zero if the stock approaches or falls below a baseline biomass. This strategy may be comparable to the way in which biological feedback mechanisms underlie natural predator-prey relationships for this type of life history pattern; for example Bakun (1996) suggested that an intermittent temporal ‘boom and bust’ pattern of variability may impart some long-term advantages to populations, by allowing for a higher average biomass over time than might be maintained in a ‘steady-state’ system in which predation pressures crop down forage species.

¹⁴ The cutoff and harvest rate levels for sardines under this approach were arrived at through simulation modeling (based on Jacobson and MacCall 1995) in which periods of good and poor recruitment success occurred in regimes of approximately a decade, with an additional weak 60 year cycle in abundance based on paleo-ecological data (PFMC 1998).

Bakun suggests that under such a scenario, the yield of many species, indeed of many ecosystems, may be unsustainable from the perspective of stock, species or ecosystem productivity. Under the PMFC type of management approach, the allowable harvest during such periods is very low or zero, while during periods of high productivity and abundance the allowable harvest can increase substantially.

Perhaps the most contemporary additions to traditional harvest methods to date are those that incorporate marine protected areas (MPAs), or rotating harvest areas, into management strategies. MPAs have been increasingly proposed as critical tools to the future management of both sustainable fisheries and the maintenance of biological diversity; in short a key element of marine resource management in general (Roberts 1997, EPAP 1999, Murray et al. 1999, Murowski et al. 2000, Roberts et al. 2001). The advantages of MPAs as management tools for conservation purposes, at least for species that are not highly migratory or mobile, they offer a form of insurance for future against both overexploitation and recruitment overfishing, the truncation of age distribution, and protection of non-target species and habitat structure from impacts of fishing gear. The potential for fisheries enhancement from reserves (particularly with regard to the production of larger, older fish) is controversial, but has been demonstrated in several instances (Roberts et al. 2001). In other instances, the prospect of increasing profitability to many fisheries through rotating harvest areas has also been discussed, for example rotating closures are being implemented in the scallop fisheries off of New England largely as a result of observations of dramatic increases in both abundance and size of Atlantic Scallops that result from relatively short periods of closure (Murowski et al. 2000). Closed areas are increasingly becoming a necessity of crisis-based management efforts as well, for example large closed areas have been created in a more ad hoc fashion to protect overfished species; in the California Current huge swaths of the Continental shelf were recently closed as an emergency measure to protect severely depleted rockfish species such as Cowcod, Bocaccio, Canary and Yelloweye rockfish. In all of these examples, reserves offer an ecological buffer, or insurance, of part of a stock from the impacts of fishing, and thus minimize the risk of catastrophic stock collapse.

Clearly, new approaches towards fisheries and marine ecosystem are inevitable, and although both single-species approaches and reference points are but one part of a larger toolkit for managing marine fisheries and resources. . Hilborn (2002) suggests that far too much time has

been spent defining, redefining and implementing reference point based management strategies, arguing that “Spending time on reference points is like rearranging the deck chairs on the Titanic- a perfectly sensible thing to do in the absence of more pressing issues.” Instead, what is needed are management procedures that are robust to large levels of uncertainty in stock sizes and fishing mortality rates, both from the perspective of ecological and economic sustainability. Precautionary buffers (particularly for forage species) and insurance in the form of threshold biomass levels and marine reserves are clearly appropriate steps in that direction.

3 Shortcomings of Reference Point Based Fisheries Management

A tremendous range of potential shortcomings and unintended consequences either exist or are thought to exist as a result of the application of management strategies based on such objectives or reference points. This section summarizes some of the key elements thought to be relevant to managing marine fisheries sustainably. Some of these, such as error, uncertainty and risk and some of the consequences of climate variability, have been explicitly considered in deriving reference points and management advice for individual stocks. Most others have the potential to be considered in the management process, although they are rarely explicitly considered now, such as the demographic and evolutionary impacts of fishing on populations and species, and impacts resulting from interactions between climate forcing and trophic relationships. Reviews by Jennings and Kaiser (1998), Hall (1999) and Mangel et al. (2000) offer greater detail into large-scale ecological and ecosystem consequences of fishing over a broad range of topic areas, including habitat impacts, evolutionary and demographic changes to populations, community impacts (such as “fishing down the food web), trophic cascades and impacts of fishing to other top trophic level predators/competitors. This section concludes with a brief summary of potential interactions between fishing impacts and other external forcing mechanisms on marine ecosystems.

3.1 Error, Uncertainty and Risk

One definition of uncertainty is the “incompleteness of knowledge about the state or process of nature,” this in contrast to statistical uncertainty which is often described as “stochasticity or error from various sources as described using statistical methodology.” Most stock assessments and other fisheries modeling efforts include some attempt to estimate quantitatively known sources of error, particularly observation (measurement) and process (generally considered ‘environmental’) error, however some other sources of error are more difficult to address. The application of the Precautionary Approach has been described as one way to deal with uncertainty and risk. In U.S. fisheries management, the precautionary approach has been defined in its most concise form as “judicious and responsible fisheries management practices, based on sound scientific research and analysis, proactively (to avoid or reverse overexploitation) rather

than reactively (once all doubt has been removed and the resource is severely overexploited), to ensure the sustainability of fishery resources and associated ecosystems” (Restrepo et al. 1999). That fisheries management effort in the U.S. are more precautionary as a result of the Sustainable Fisheries Act of 1996 seems clear, yet equally clear is the fact that a great deal of uncertainty and risk with regards to both population and ecosystem impacts remains.

3.1.1 Observation and Process Error

Observation error, or measurement uncertainty, is the error in the observed quantities (such as catch per unit of area or effort) in survey and fisheries data. Any use of survey or fishery data must reconcile numerous assumptions in order to develop a meaningful index. Amongst these are assumptions related to the availability of the target population in the survey area, which is often complicated by seasonal and interannual variation in distribution patterns; and the vulnerability of the target species to sampling gear, which is often complicated by behavioral characteristics of the target species. For example, species may have daily (diurnal) migrations, seasonal migrations and interannual variability in distributions that are associated with environmental conditions (Gunderson 1993). When these assumptions can be reconciled, then observation errors are sometimes considered the ‘best understood’ type of uncertainty as it generally can be characterized directly from the data and statistical theory, and consequently accounted for in assessments. For example Caddy and Mahon (1995) estimated that most biomass surveys for temperate water shelf fisheries tend to have coefficients of variability (CVs)¹⁵ ranging from 35 to 40%. Biomass surveys for many key species in the Bering Sea and Gulf of Alaska tend to be consistent with this range of variability, for example the overall CV from 2001 groundfish biomass surveys for walleye pollock in the Gulf of Alaska is estimated at 0.3 according to Dorn et al. (2001); although the CV tended to be higher or lower by region and depth, a factor important to allocating total allowable catches spatially in proportion to biomass (NMFS 2000).

It is important to recognize that observation errors are not limited to catch statistics, but are intrinsic properties of all fisheries data, including length and age estimations, maturity schedules

¹⁵ The coefficient of variability, or CV, is the standard deviation divided by the mean and is an often used statistical gauge of how variable, or noisy, data from a given survey or source is.

and selectivity estimates. Bias is another source of observation error that is much more difficult to account for; bias tends to be more of a problem in statistics obtained directly from fishing activities and generally results from misreporting (usually underreporting) of catch, discard and effort data. Patterson et al. (2001) found that such biases led to substantial problems in trying to characterize uncertainty, especially in instances where misreporting and discarding were unpredictable responses to management actions. Observer programs that put fisheries biologists on board fishing vessels to collect fisheries data can result in better quality fishery-dependent data, as well as a means to evaluate bias in reported data. However, such programs are typically expensive and not without problems of their own. In addition to misreporting, there are also changes associated with measuring effective effort, as both technological innovations, vessel fishing power and learning lead to catch per unit effort (CPUE) data that is often unreliable (Caddy and Mahon 1995).

Process error is usually best described as the underlying, environmentally driven stochasticity in population dynamics that results from climatic and oceanographic variability. Variability in climatic and oceanographic processes, as well as ecological interactions, leads to uncertainty in understanding the behavior of population processes such as recruitment or growth rates. As an NRC (2002) review on the state of fisheries science in the U.S. suggested, "If NMFS could conduct a complete census of the fish in the ocean, scientists and decision-makers would still have to deal with uncertainties of natural variation in populations resulting from processes of birth, death, growth, immigration, and emigration, each of which is affected by environmental factors in ways that are not entirely understood." The extreme example of this source of 'error' is that there seem to be a large number of fish populations in which recruitment variability is so high that the abundance is based almost entirely on occasional, very large year classes; such characteristics have long been thought to be incompatible with management strategies that are based on stationary assumptions of predictable spawner-recruit relationships (Beddington et al. 1984). Additionally, it is generally well accepted that stocks become more vulnerable to environmental variability as exploitation rates increase, even independent of an increase in the variability of recruitment success. Thus, as stocks sizes are reduced, process error likely increases, and if observation error remains constant while mean biomass levels decline, the relative error (CV) may increase as well. All of these factors suggest that the amount of error in a stock assessment increases as stock sizes decline.

As an example of how error is quantified in stock assessment results, the 1999 assessment for Eastern Bering Sea pollock (NMFS 2000, citing Ianelli et al. 1999) included estimates of uncertainty associated with three alternative fishing mortality rates; F_{MSY} , $F_{40\%}$ and $F_{30\%}$. The $F_{40\%}$ strategy suggested a point estimate of 1.013 million metric tons as the appropriate yield, yet the 50% confidence limits for this estimate were 0.6 million to 1.7 million metric tons and the 95% confidence limits were between 0.2 and 3.0 million metric tons. The expected probability of overfishing with the target yield was 30% in that example, but perhaps most important is that this stock is the only one assigned to the highest data-quality tier in the North Pacific Council jurisdiction.

3.1.2 Model Uncertainty

Most fisheries models are based on the view of both populations and ecosystems as stable systems which, when perturbed, will tend to return towards their equilibrium state. Hilborn and Walters (1992) suggest that this “mythological balance of nature” is one of the greatest flaws of fisheries management today, suggesting that “even though few practicing ecologists or fisheries scientists would agree that this myth has much to do with reality, almost all fisheries theory is based on it!” This view is increasingly evident in current thought and literature, which suggests that the ability to accurately predict and control population trajectories is limited (Holling and Meffe 1996, EPAP 1999, Mangel et al. 2000, Rice 2001). As discussed earlier, the observation by Hutchings (2001) that many heavily depleted fish stocks have failed to recover also suggests that the resilience inferred in many population models may be too optimistic.

Schnute and Richards (2001) discusses the role of models and model failures in numerous fisheries collapses to suggest that quantitative stock assessment methods provide no guarantees that a given fishery will remain sustainable. Their evaluation of the roots of fisheries science principles is directly relevant to the statement by Roberts (1997) that “if engineers adopted the same approach by building bridges strong enough for just the average flow of traffic, they would soon share the reputation that fisheries managers enjoy.” They argue that while a civil engineer does not have to reject the science of mechanics when a building collapses, fisheries scientists are hampered by considerably less precise and reliable first principles, thus fishery systems

cannot be modeled as precisely as physical systems.¹⁶ Consequently, any ability to predict stock collapses and other crises are dependent on a broader perspective than the simplifying assumptions of equilibrium models. Additionally, the inability to exactly achieve a target harvesting strategy through a failure to control or enforce management efforts is yet another form of uncertainty, and one often attributed to a large number of stock collapses that might not have occurred had assessment advice actually been followed (Caddy and Mahon 1995).

Understanding the uncertainty in a model becomes particularly challenging with contemporary stock assessment models, which typically use tens to hundreds of parameters estimated with complex fitting routines to obtain the best numerical fit to existing data. As Hilborn and Walters (1992) and others will suggest, any model that does assume fixed parameters will never be precisely correct, as parameters such as natural mortality, selectivity, catchability and others are rarely fixed in time and space. Yet in the absence of improved information, such assumptions are necessary in constructing assessment models. Thus scientists conducting stock assessments must determine “the best among several imperfect choices for making predictions given whatever limited historical information is available.” Patterson et al. (2001) call this the ‘conditioning’ of an estimation, a process necessary to arrive at an estimate or forecast. The result is that any uncertainty presented for management purposes is but a part of the true overall uncertainty. Thus, when a model suggests that a given harvest rate has a 50% probability of resulting in a biomass level of $B_{40\%}$, such information is based on thousands to millions of simulations in which a wide range of plausible parameter values are estimated, but in which the true dynamic nature of such parameter values can never be fully understood. It is important to recognize the tails of such distributions as well, for often a 50% probability of achieving $B_{40\%}$ is associated with a real (say 5 to 10% for example) probability of resulting in biomass levels below $B_{20\%}$. Ensuring that managers understand these risks is a critical task of stock assessment authors.

¹⁶ Another example Schnute and Richards (2001) offer is of a university student taking a course in physics and another in fisheries. In the physics course the student is exposed to the constant G_0 , a gravitational constant that is a part of Newton’s law and considered applicable throughout the universe. By contrast, in the fisheries course the student is exposed to the parameter M , natural mortality, which is by necessity is considered constant in nearly all fish population models despite the acknowledgement that it may vary tremendously with age, behavior, predator and prey abundance and environmental conditions. Yet the student may come to believe that the lessons and models of both courses have similar applications to the real world.

Conditioning might be considered almost as much an art as it is a science, and the field itself is a challenging one that is both extreme in its demands of quantitative and analytical abilities yet rich in innovation and originality. However the failure to adequately make these increased risks clear to decision makers may result in an unfounded faith in the bounds of uncertainty that are presented. For example, Caddy and Mahon (1995) argue that reference-point based fisheries management has provided decision makers with an excuse to avoid difficult decisions, by allowing them to focus only on the uncertainties and risks in terms of the error surrounding particular values for reference points and the probabilities of achieving those values under alternative fishing strategies. Part of the problem may be institutional, as Longhurst (unpub) suggests “fisheries administrators (and politicians) need to appear and sound confident of the scientific basis for their decisions- so the apparent precision of stock assessment models is a bonus rather than something to be questioned. That it may mislead doesn’t seem to have entered anybody’s head in the past.” Yet given high profile stock collapses, such as the collapse of Northern cod that occurred despite intensive survey, data collection, modeling and management efforts, it has become clear that the uncertainties of fisheries science are substantially greater than previously believed (Hilborn et al. 2001).

3.1.3 Coping with Uncertainty and Risk

In the US, the legal and institutional philosophy regarding uncertainty and risk is that it is the job of the scientists and biologists who conduct assessments to quantify and define the level of uncertainty and risk in data, assessments, and consequent management advice, and the job of the decision makers to determine the appropriate level of risk taken in making the consequent management decisions (Restrepo et al. 1999). As a result of growing calls to address uncertainty and risk in decision-making, and the concurrent advances in the development of integrated and Bayesian assessment methodologies (as well as computing power), more formal means of integrating and evaluating uncertainty from observation and process error, parameter uncertainty and even management measures have evolved (Punt and Hilborn 1997, Hilborn et al. 2001, Patterson et al. 2001). However as Mace (2001) points out, the inclusion of more data often means that there are more ways of estimating and characterizing uncertainty; leading to the illogical reality that confidence intervals often become wider with additional data rather than more narrow.

Some of the logic behind this delegation of the responsibility for addressing risk lies in the premise of what the risk actually relates to. From a single species perspective, risk is usually characterized as a weighting between the risk of stock depletion or collapse (setting catches too high, or overfishing) which would (at least by US law) have to be followed by reduced catches to rebuild stock biomass, and the risk of foregone yield (setting catches to low) in which case both profits and presumed benefits to society are lost. Although managers and decision makers often tend to be “risk prone” when making decisions, considerations for the stability of the industry and supply of fish often help to temper extremely risky decisions (as do National Standard guidelines for avoiding overfishing). However with respect to the levels of risk that decision makers consider, several important factors are often overlooked. Generally, decision makers operate under the assumption that if a stock is overfished as a result of a bad decision, the reduction of catches in the future will result in stock recovery; an assumption being increasingly question in light of many stock collapses that have yet to show signs of rebuilding (Hutchings 2001). Additionally, the subsequent impacts of stock declines beyond those targeted to dependent species and ecosystems are rarely considered unless required by law (such as the ESA or MMPA), and even then the potential consequences are difficult to evaluate or quantify.

The precautionary approach is increasingly cited as a means for confronting and coping with these sources of uncertainty and risk (Parkes 1999, Restrepo et al. 1999, Mace and Gabriel 1999, Hilborn et al. 2001) and while a thorough review of the concept is beyond the scope of this review, Hilborn (2002) suggests out that reference points have become wrongly identified with the precautionary approach to fisheries management in the U.S., Canada and Europe. Instead he argues that a true precautionary approach should be about the management process rather than reference points; “The vast majority of the world’s fisheries are not precautionary- not because the reference exploitation rates are too high but because catch cannot be measured or catch limits enforced, because abundance cannot be accurately estimated, or because rules do not state how catches will change in relation to stock size.” However, while acknowledging that managers have proven quite willing to make extremely risk-prone decisions in the face of uncertainty,¹⁷

¹⁷ Mace (2001) includes two highly compelling examples of the willingness of managers to make highly risk prone decisions; including one in which managers opted to use F_{\max} as a proxy for F_{msy} , consequently setting F_{\max} as the target rather than the limit and furthermore allowing a harvest rate that had a 97% chance of exceeding this target. The resulting lawsuit set the legal precedence that targets should have at least a 50% probability of being attained in setting quotas.

Mace (2001) suggests that the use of reference points as indicators of overfishing has in fact been successful in reducing (albeit not eliminating) overfishing, in a large part due to the fact that the consequences of exceeding biological limits can be readily portrayed and appreciated by decision makers in terms of risk to the resource. This success is significant, for even though it may not consider all real or potential risks to exploited populations and their ecosystems, even the most vocal critics of the single-species paradigm acknowledge that an ecosystem-based approach is unlikely to be an improvement in areas where single-species based management advice has not been effectively implemented in the first place (Pauly et al. 2002).

3.2 Evolutionary and Demographic Impacts of Fishing

In their essay on fishing as an evolutionary force, Stokes and Law (2000) suggest that “To an evolutionary biologist fishing is a massive uncontrolled experiment in evolutionary selection”. These authors, and numerous others cite a greatly increasing body of literature that clearly demonstrates that fisheries result in substantial changes in both genetic and demographic characteristics of fish populations. With regards to genetic and phenotypic consequences, well-documented alterations in size at age, size and age at maturity, and total fecundity are common,¹⁸ and some examples even suggest changes in body shape, alterations in heritable patterns of distribution and migration and even changes in avoidance behavior. The body of research in this field is substantial, although most reviews indicate that the vast majority of research has focused on the evolutionary consequences of fishing to the heavily fished ecosystems of the North Atlantic (see extensive reviews in Stokes and Law 2000, Law 2001, and Heino and Godø 2002; but see also Ricker 1981 for a classic example in Northeast Pacific salmon fisheries). In terms of demographic changes, the truncation of age distributions that directly result from fishing down populations is the primary factor that acts as such an evolutionary force, and a growing body of evidence suggests that the consequences to the truncation of age structure include reduced relative spawning effort and an increased vulnerability of populations to overexploitation

¹⁸ While evidence for such changes is overwhelming, there are challenges associated with disentangling environmental changes in size and maturity at age from those resulting from fishery-induced selection and genetic change. Individual growth rates can increase as stock abundance decreases as a result of increased availability of food, and growth rates tend to vary in both directions as a result of a range of environmental forces. For example, the average body size at age of Pacific hake declined tremendously between the early 80s and the mid-90s, a period characterized by a large hake population and poor environmental conditions (low productivity, warmer ocean temperatures), yet size at age has increased to previous levels over an extremely short period of time since 1999 when ocean temperatures cooled and productivity increased.

(Longhurst 1998, Fogarty et al. 2001). Because the demographic consequences of fishing are closely related to the evolutionary impacts, the consequences of both are difficult to disentangle.

3.2.1 Evolutionary Impacts of Fishing

Fishing pressure is widely accepted to be a form of artificial selection (Mangel et al. 1993) and the most predictable result is an evolution towards smaller size or younger age at reproduction resulting from higher mortality rates for faster growing individuals. As early as 1912 it was noticed that fish caught in the early or developing years of a fishery tended to be larger at age than those caught in more recent years (Lee 1912, as cited in Mangel and Stamps 2001). The logic behind this is quite simple, when mortality increases as a result of size-selected fishing (typically larger fish are more selected by a given fishery than smaller fish, especially as larger fish generally have a higher market value); faster growing individuals are removed at higher rates than slower growing individuals. The result is that slower growing animals make up a greater percentage of their age group; and the population in question is selected to be smaller at a given age over time. The same logic applies to the selection of earlier ages at maturity; if a fishery catches disproportionately more larger fish than smaller fish, then fish that mature earlier will have greater reproductive output and consequently leave more offspring to future generations (Law 2001). Clearly such evolutionary processes should not be exclusive to fisheries but rather to all selective forces acting on a population. Although examples in which factors other than fisheries have been linked to such changes are rare, Mangel et al. (1993) cite early work in Quebec, Canada (Power and Gregoire 1978) in which lakes, which supported landlocked harbor seals, had brook trout populations, which matured at considerably smaller sizes than lakes without harbor seals.

Equally clear is that selection can work in various directions depending upon the nature of the fishery. For example Heino and Godø (2002) cite a body of work specific to Northeast Atlantic cod which suggests that selection pressure for delayed maturation resulted from historical fishing effort being focused on spawning grounds; by delaying maturation these cod postponed exposure to fishing mortality and were consequently more fecund (had a greater reproductive output resulting from larger size at maturity) when they were exposed to fishing pressure. Before the 1940s these cod had a median age at maturation (age at which half the population are mature) of

greater than ten years, yet following alterations in fishing patterns that made fish vulnerable at all life stages both the age and size of maturity have declined substantially. Heino and Godø (2002) also cite examples that suggest that spatial patterns of fishing effort may lead to changes in the heritable patterns of distribution and migration in stocks, as evidenced again by cod stocks in which traditional inshore spawning areas have gradually been diminishing in importance as a result of centuries of high exploitation near fishing communities.

Conover and Munch (2002) demonstrated just how rapidly selection could act on the genetic variability of populations with laboratory-reared populations of Atlantic silverside (*Menidia menidia*) that were subjected to two types of size-selected mortality (higher mortality for both larger and smaller fish) as well as size-independent mortality. They found that the populations in which larger individuals were harvested more intensively produced the highest initial yields, but the average weight of fish in those populations soon began to drop. By contrast, the small-harvested populations began with low yields, which slowly began to increase and ultimately (by the 4th generation) became nearly twice that of the large-harvested population. Additionally, the smaller-harvested lines generated substantially greater spawning biomass and potential than both the large and randomly harvested lines. The authors suggested that the differences in growth rates were in part a result from changes in per capita rates of food consumption, and that the effect could be partially obscured (in the short term) for some stocks as a result of the increased growth resulting from lower fish density (reduced competition for forage).

Their results speak not only to the necessity to consider evolutionary consequences, but also to the observation that the consequences could be detrimental to humans as well as fish. Quite simply, these evolutionary consequences can reduce the sustainable yield of a population by decreasing the age at maturity and consequently reducing the relative amount of somatic growth in a population relative to reproductive effort. As Conover (2000) suggests, “Yield... is not a currency that is crucial to fitness. From the fishes’ point of view, the goal is maximizing the relative contribution of genes (not biomass) to succeeding generations. Fisheries management plans, and the stock assessments on which they are based, are, therefore, non-Darwinian: they ignore the prey’s co-evolutionary response to the effects of harvest.” Thus, despite the fact that the long-term genetic consequences of size-selective fishing mortality may be very substantial to exploited populations, they may ultimately prove even more detrimental to the humans and

communities dependent upon such resources; particularly where larger fish are significantly more valuable than smaller ones. Moreover, Law (2001) cites evidence that reversing such effects could be more difficult than inducing them in the first place, as it may be easier to select for patterns of early maturation than for late maturation. On the bright side however, Heino and Godø (2002) point out that such adaptations to exploitation do enable fish to sustain higher fishing pressure and thus, all else being equal (i.e., exclusive of the extremely adaptive behavior of most fishermen), can reduce the risk of total stock collapse. In any event, it is increasingly clear that ecological and evolutionary considerations in traditional stock assessment methods will have to be considered if ecological consequences to evolutionary integrity are to be truly considered in managing marine resources.

3.2.2 Demographic Changes to Fish Populations

As discussed above, the reason that fishing acts as an evolutionary force is because fishing truncates the age distribution of a population, effectively an unavoidable and widely recognized consequence of fishing, yet one that could potentially undermine evolutionary adaptations responsible for a given species success (especially under scenarios of overexploitation). Figure 3.1 shows an example of the expected (targeted) impact to the distribution of biomass at age for Atka mackerel under an $F_{40\%}$ harvest strategy, taken from Witherell and Ianelli (1997). The figure shows proportionally greater declines of older (and larger) individuals under the fished scenario, with the biomass of age 10+ individuals being barely 5% of the biomass of age 10+ individuals in an unfished population.

The significance of longevity and consequent age distribution was considered by Leaman and Beamish (1984) who argued that the failure to consider the role of longevity in managing many slow growing marine species in the Northeast Pacific could lead to management failures. They argued that unexploited stocks of species characterized by large adult biomasses in the range of 30 to 50 years of age are simply maintaining themselves within the dynamic bounds of their ecosystem, bounds that are inconsistent with intensive harvests. Conover (2000) also suggests that long reproductive life spans lead to large quantities of “stockpiled” adult biomass stockpiled that are highly vulnerable to overexploitation. He too argues that truncation of the age

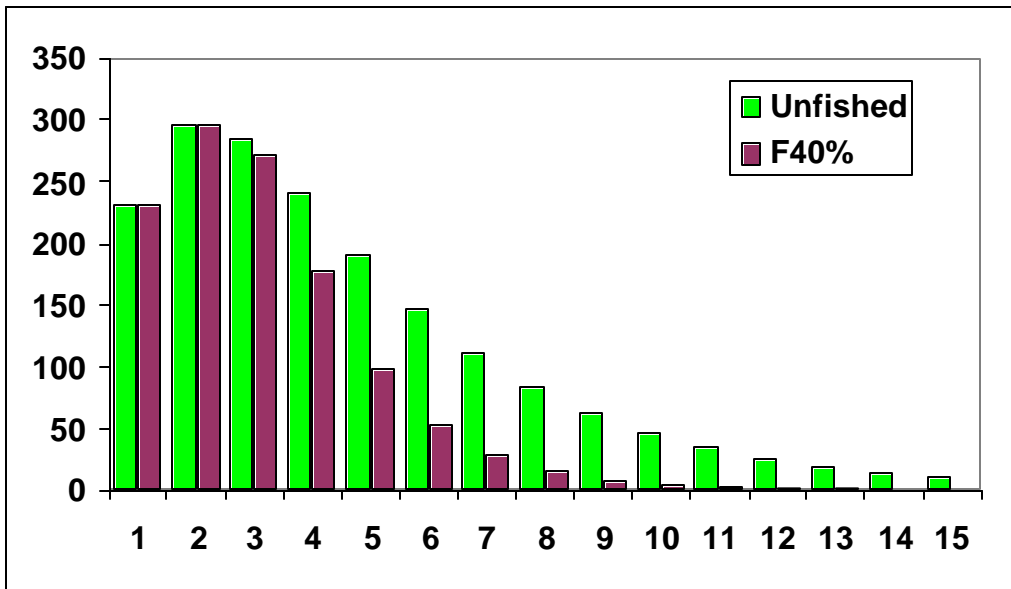


Figure 3.1: Consequences to the biomass-at-age distribution resulting from application of $F_{40\%}$ to the hypothetical Atka mackerel stock presented in Witherall and Ianelli (1997).

distribution of such stocks reduces reproductive lifespan, and consequently nullifies bet-hedging as a viable life history strategy compared with what existed prior to fishing.

Longhurst (1998) delivers an eloquent indictment of the effects of truncating age distribution in the infamous collapse of Canadian cod fisheries, arguing that “it is surely axiomatic that the natural population age structure of any species- whether of cods or copepods- must have evolved (within the physiological capacity of each species) to optimize long-term persistence, and maximize occupation of habitat in competition with other species”. He cites much earlier work by Lotka (1925) who argued that the variability of the age structure of natural populations is viable only within limits, and that if pushed beyond such thresholds the ability of populations to persist or recover is limited; Longhurst refers to this as the “boundary of sustainability.” In a later paper (Longhurst 2002) he argues that the relationship is essentially one between recruitment variability and age structure, in which temperate water fish tend to experience considerably greater variability in recruitment, and subsequently are sustainable only when something approaching the natural age composition can be maintained. Doing so, Longhurst argues, will require that fisheries managers and biologists to formally consider age structure, and that the fishing industry find the means to operate with a variable resource as allowable landings fluctuate.

Beyond the potential consequences of altering age structure, there exist several flawed assumptions of management based on typical spawning stock biomass reference points, as related to age structure and effective reproductive output. The typical assumption of most stock assessments is that the effective spawning potential of a fished population is a sum total of the spawning biomass (or spawning output if that data exists), as estimated by the number of females at age multiplied by the percent mature at age and size at age. In simplified terms, this assumes that the spawning potential of five spawners weighing one kilogram each is equivalent to one spawner weighing five kilograms. Larkin (1977) cited early literature that suggested the consequences could include declines in the quality of eggs produced in cases where spawning populations could consist primarily of (increasingly younger) first and second time spawners. Since then a growing body of research, summarized in Trippel et al. (1997) and Murowski et al. (1999 and 2001) has revealed how these assumptions discount several important facets of reproductive biology that have only recently begun to be quantified.

For example, ongoing laboratory research with Atlantic cod suggests that first and second time spawners breed for shorter periods of time, produce fewer egg batches, and produce smaller size eggs with lower fertilization and hatching rates (Murowski et al. 2001). Although the physiological basis for these variations in spawning success are not known, it is recognized that many of these first and second time spawners are fish that have been selected for earlier sizes and ages at maturity as a result of fisheries selectivity. Murowski et al. (2001) modeled the estimated spawning stock biomass of Georges Bank cod both under standard assumptions and under assumptions of variable egg production, variable egg hatching rates and variable larval survival, and found that accounting for these factors led to considerably lower estimates of spawning intensity. Although little research into these effects has been published on Northeast Pacific fish species, revisiting our earlier example of Atka mackerel (figure 3.1 based on Witherell and Ianelli 1997) would suggest that under an $F_{40\%}$ harvest strategy the fraction of egg production from first and second time spawners (estimated at ages 3-4) would increase from 25 to 49%. The implication would be that the effective spawning potential could be lower than what is estimated when treating all units of spawning stock biomass as equivalent.¹⁹

¹⁹ There is an interesting twist to the implications of this phenomena, for if “effective spawning biomass” is found to be reduced for a given stock, the observed recruitments for that stock would actually imply a more compensatory relationship than would be assumed by simply assessing the measured spawning biomass.

Other studies have suggested that the truncation of age structure could reduce recruitment potential by shortening the duration of the spawning in populations for which the timing of spawning varied between older and younger fish, as found by Hutchings and Myers (1993) for Grand Banks cod. Researchers at Oregon State University²⁰ have found that older female Black rockfish tended to extrude larvae earlier in the season, followed by younger fish later in the season (the reverse of the pattern seen by Hutchings and Myers). As many rockfish species have demonstrated extreme variability in recruitment success, thought to be linked to the highly dynamic environment in which they live (Ralston and Howard 1995), the inference is that a broad distribution of age structure may increase recruitment potential by increasing the probability that larvae are exposed to optimal environmental conditions. Finally, there is evidence that older individuals in some populations may play a key role in migratory behavior, such that younger cohorts may be subjected to higher straying rates as they seek spawning grounds resulting from a loss of “social tradition” (Macklin 1999 and citations therein refer to studies related to Atlantic cod and herring). There are clearly a wide range of genetic and demographic considerations that have yet to be fully resolved or understood at a multitude of scales; in few if any instances have management practices been able to account for the potential consequences of such impacts in managing these resources.

3.3 Climate Variability and Fisheries

As suggested at the beginning of this review, changes in ocean conditions resulting from climate variability has been long acknowledged as a key factor in influencing recruitment and year class strength (particularly for temperate water fishes), and consequently altering the productivity of marine populations over both short and long time scales. The theme of climate induced variability is integrated into many of the evaluations and simulations of reference points done to date; from the earliest criticisms of MSY as a theory to sustain long term yield under variable environmental conditions (May et al. 1978, Doubleday 1978) to the suggestion that $F_{40\%}$ offered more of a buffer against uncertainty than $F_{35\%}$ under conditions of long-term variability in recruitment (Clark 1993). Climate processes are responsible for these “process error” variations

²⁰ This topic is the subject of Steven Bobko’s Ph.D. dissertation from Oregon State University entitled “Effects of maternal age on reproductive success in Black rockfish, *Sebastes melanops*”, for which Professor Steven Berkeley was the major advisor. The dissertation is published at OSU and the results of this work are expected to be published in the near future.

of typical stock assessment models, and climate or climate regime shifts are sometimes described as the rule changes that undermine the assumptions of stability and equilibrium for the same. Finally, as reviewed in the section above on fishery induced demographic shifts, the mechanisms that temperate water fishes have evolved to cope with climate suggest that when environmental stress is strong and recruitment weak, many such species may be unable to sustain viable populations in the face of industrial fisheries (Longhurst 1998).

Recruitment varies for an immense multitude of both density dependent and density independent reasons; including the abundance and condition of the spawning (parental) stock, intra- and interspecific competition in the planktonic community, and in response to climate forcing on the marine habitat of eggs and larvae. The vast majority of truly compelling hypothesis regarding density-independent processes are based on the impacts of physical forcing on both abiotic and biotic environmental conditions for early life history stages of marine fishes; and it was here that Hjort (1914) began the quest for answering this question; first by simply proposing and demonstrating that there was significant variability in year class strength in Norwegian herring and cod stocks over time²¹ and second, demonstrating that year-class size was not a simple function of egg production but rather a result of differential multiple causes of mortality in early life history stages. He went on to offer two potential explanations for this differing mortality; the first being the availability of adequate food resources (the timing and magnitude of phytoplankton blooms) during the critical period in the early life history stages of larvae. The second was related to the vagaries of ocean currents and the potential for the planktonic early life history stages to drift away from their appropriate habitat and thus not survive or contribute to the population. Although the processes responsible for recruitment variability have been a focus of fisheries research since Hjort's time, these two explanations remain the key principles on which virtually all density-independent mechanisms of recruitment variability have been founded.

Bakun (1996) has further synthesized the three key physical mechanisms that lead to a favorable reproductive habitat for most fishes; these being enrichment processes (mixing and upwelling),

²¹ Hjort showed that catches throughout decade-long periods were often dominated by a single year class, and by inference then the fluctuations in the abundance of many species could be attributed to the strengths or weaknesses of different year classes (and often of distinct populations) over time, rather than the "vagaries of panoeanic migrations of typological or essentialist species" as had been previously thought (Sinclair 1988).

concentration processes (mixed layer stabilization, convergence) and transport or retention processes (habitat related constraints). He calls this the ‘fundamental triad’ underlying reproductive habitat suitability; and for species to which the triad applies, recruitment tends to be greatest during periods or years in which mutually supportive combinations of these events occur. This triad synthesizes the key physical processes that are known to drive recruitment variability, and certainly holds its own as an explanation for many coastal pelagic species. The importance of such physical processes in determining year-class strengths tends to be considerably greater for temperate and subarctic species where the influence of seasonality and variability in the physical and biological environment is more significant.²²

As a simple example, upwelling zones are amongst the most productive marine ecosystems, and tend to support the highest volume (albeit generally low value) fisheries, yet interannual variability in upwelling intensity, and consequently production, can be substantial. Prior to a strong El Nino event in 1972, the Peruvian anchoveta fishery was the largest in the world, with catches approaching one fifth of the total global marine fish landings (nearly 15 million metric tons). When upwelling was reduced, productivity and recruitment plummeted, and the consequent failure to reduce fishing effort led to a collapse of the anchoveta stock as well as a multitude of dependent populations of fish, seabirds and marine mammals (Pauly and Tsukayama 1987). However the long-term climate interactions are considerably more complex than El Nino events. A growing body of evidence (Schwartzlose et al. 1999, Bakun and Broad 2002) suggests that decadal scale variability in large scale climate-ocean interactions are key driving factors for many large marine ecosystems, that shifts in species dominance, particularly between sardine and anchovy populations, seems to occur somewhat in phase across ocean basins, and that the excessive fishing of populations in either decline or recovery phases can dramatically alter the natural succession of species and consequently the structure and function of these ecosystems.

²² For example, Houde (1989) found a strong relationship between temperature (and subsequently latitude), the length of larval stage durations for fishes and the subsequent coefficients of variations in recruitment for different stocks. The key point of his work was that there was no significant difference between temperate and tropical fish larvae with regards to growth efficiency and temperature/latitude, rather the rapid growth rates observed in the tropics corresponded to increased consumption rates. Subsequently, the lower growth rates observed in cooler water species were shown to be associated with longer stage durations and higher daily mortality rates. While Houde uses these results to infer that density-dependent growth or mortality is more likely to have an effect at high latitudes due to longer larval stages, this trend also suggests that higher latitude species considerably more vulnerable to density-independent processes resulting from physical forcing.

In the Northeast Pacific, the recent literature has been saturated with studies showing significant linkages between climate and the organization of the marine and estuarine ecosystems. Many of these studies, such as Hollowed and Wooster (1995), Mantua et al. (1997), Francis et al. (1998) and Hare and Mantua (2000) examine the relationships between Northeast Pacific atmospheric indices and production responses such as survival and production of salmon smolts (particularly an apparent oscillation between salmon production in Alaska and off of the West coast of the U.S.) and year class strengths (recruitment) of a wide range of groundfish populations. Other studies have explored connections between variability in ocean-atmosphere interactions and subsequent bottom-up marine biological response. Brodeur and Ware (1995) demonstrated an apparent doubling of biomass for zooplankton, forage fish and squid in the subarctic North Pacific in the 1980s relative to the 1950s, and Polovina (1995) found similar trends of increased productivity linked to changes in the strength of the Aleutian Low Pressure System. McGowan et al. (1998) attributed significant long term declines in zooplankton populations in the California Current over the same period to increased water temperatures that resulted in an intensification of stratification and a reduction of nutrient regeneration into surface waters.

The consequences of the interactions between marine populations and climate are that factors affecting the productivity of marine resources and ecosystem structure should be directly accounted for in fisheries management strategy. Levels of sustainable yield and exploitation, regardless of how they are defined, are directly tied to the state of the environment and its effects on productivity of marine populations. Coping with this challenge was a problem recognized by Hilborn and Walters (1992) who suggest “the role of stock assessment is not to make best guesses at MSY, but rather to help design a fishery management system that can respond to the types of variability we see in nature.” Generally, it is widely (and intuitively) acknowledged that environmental changes that result in an overall reduction in the productivity of a marine resource can result in the decline or collapse of a population under levels of exploitation that are sustainable under more favorable environmental conditions. In fact, Rice (2001) suggests that “whenever a regime shift is suspected, it would be wise to reduce fishing mortality of fully

exploited systems until the productivity of the new regime is understood.”²³ Rather than consider the effects of exploitation and climate change on marine populations as distinct and separate factors, future management efforts must instead recognize the interactions between the environment and human activities, and adjust management approaches accordingly. Most fisheries reference points, regardless of how precautionary their application, fail to do so.

3.4 Ecosystem consequences and trophic interactions

It is irrefutable that fisheries remove fish from the sea that would have otherwise entered energy pathways within the ecosystem in which they exist, and that as a consequence of fisheries the production of fished species available for predators declines. The Panel on ecosystem-based fisheries management (EPAP 1999) suggested that when fishing is examined from an ecosystem context the rationale for surplus production is unclear, as before the advent of fisheries all production was recycled within ecosystems. Interpretation of this statement must be made with caution, as the intent was to infer that the consequences of any fishing include some level of ecological changes among competitors, prey and predators, and that such consequences are often poorly accounted for in single-species estimates of surplus production. While it is true that any fishing activity can be expected to have some impact on an ecosystem, the focus of the report was in reference to the potential for ecosystems to shift into vastly different, potentially unproductive alternative states of stability following massive perturbations. The key message was that the levels of exploitation that might trigger such changes were unknown, and probably varied dramatically between ecosystems.

Evidence for large scale shifts in community and ecosystem structure as both direct and indirect consequences of intensive fishing have been widely and thoroughly documented in ecosystems ranging from Polar to tropical waters; and temperate shelf communities in particular have been widely documented to undergo large scale shifts as a result of intensive removals of target and non-target species (Hall 1999, Jennings and Kaiser 1999). Pauly et al. (1998) has evaluated this particular theme on a global scale, by demonstrating that changes in community composition and trophic webs as indicated by global fisheries landings data may be resulting in a phenomena he

²³ Rice (2001) goes on to describe in detail five basic environmentally driven processes that make ecosystems dynamic and to evaluate how these processes may or may not be consistent with contemporary population theory as used in most single and multi-species models used for marine populations in highly dynamic ecosystems.

called ‘fishing down marine food webs’, in which both individuals and species of larger size, greater age and higher trophic levels are gradually removed by fishing and replaced by smaller younger individuals and even whole communities of faster growing species that feed at lower trophic levels. That this may be undesirable for a variety of both ecological and economic reasons had been noted much earlier by May et al. (1979), who observed that “relatively large yields of stocks low on the trophic ladder usually require that their predators be driven to low levels.” These authors concluded that while MSY was a useful concept for considering species or stock behavior at higher trophic levels, MSY was not appropriate for species or stocks that tended to have strong interactions.

Additional ecosystem impacts have often been inferred as a result of trophic cascades; in which declines of high trophic level species (keystone predators) have cascading impacts through food webs to the abundance, productivity and species diversity of lower trophic levels. Clear examples of trophic cascades appear to be more common for semi-enclosed ecosystems such as lakes and environments with interactions on two-dimensional surfaces such as intertidal or subtidal environments (Paine 1969, Tegner and Dayton 2000). One often cited example is the case of sea otters in the Aleutians, in which the vast majority of the population was removed first by man (Simenstad et al. 1978) and perhaps more recently by increased predation from Orcas (Estes et al. 1998). In both instances, these removals appear to have led to an increase in abundance of a key prey item, sea urchins, which in turn resulted in a decline in kelp. The loss of kelp negatively affected the communities dependent upon kelp for both forage and cover, leading to a substantial restructuring of species interactions beyond the kelp forest community and throughout the coastal environment. As one ventures further from these environments, the evidence for trophic cascades begins to become spottier, although Van der Elst (1979) reported a classic example of top-down control of a coastal ecosystem off of the Natal coast in South Africa. In this case, increased mortality of large sharks resulted from the use of shark nets to protect bathers, which subsequently caused an apparent increase in the abundance of smaller dusky and milk sharks on which they preferentially fed. This increase of smaller sharks resulted in a substantial decline in catch per unit effort of several populations of teleost fishes that were both commercially and recreationally important to coastal communities in the region.

Returning to a simple example of the expected consequences of fishing to a single population's interaction with its ecosystem, we can consider again to the Atka mackerel example presented in Figure 3.1. This model can be used to estimate the flow of biomass to the ecosystem that would result from the steady state populations of the Atka mackerel stock without fishing and under an $F_{40\%}$ management strategy, by partitioning total mortality between natural mortality and fishing. What we observe is comparing the two is that with these fishing scenarios there is roughly 65% of the biomass flow to the ecosystem as would be expected without fishing. Yet if we focus only on adults (defined for these purposes as age 4+, as this age is over 50% mature and nearly fully vulnerable), we see that from these age classes only 35% of the potential energy flux to the ecosystem occurs with fishing. In other words, if a single predator was dependent on adult Atka mackerel it would find that the available biomass of its prey had declined by 65%. An extension of this logic would suggest that under scenarios where spawning biomass was 20% of that at a perceived equilibrium would result in a loss to natural mortality processes of less than 20% of that at B_0 .

The extent to which predators that would have likely eaten such fish can adjust their feeding habits to compensate for a reduced availability of prey is very poorly understood; if predators compensate by simply eating the same volume of fish they would have eaten otherwise, relative natural mortality would increase, stock assessment model assumptions would be violated, and the stock would be at greater risk of collapse. This mechanism has been referred to as a "predator trap", and it has been suggested that such a mechanism may partially account for the failure of Newfoundland-Labrador cod populations to recover, as per capita consumption by harp seals may have remained close to constant despite large-scale declines in cod and concurrent increases in seal abundance (Bundy 2001). An example of the converse is given in Jennings and Kaiser (1999), who suggest that declines of grey seals (as well as impacts to cod and seabirds) in the Barents Sea were directly related to the collapse of capelin stocks following intensive fishing. In this instance, many seals died of starvation over relatively short time periods, and many others made unusual migrations that often resulted in increased mortality from gear interactions. Yet these authors also suggest that such dramatic consequences should be limited to specialists with limited prey opportunities, and that higher trophic level predators rarely have such tightly coupled predator-prey relationships if alternative prey opportunities exist. However the fact that

fisheries do compete with other predators is clear, and it is reasonable to assume that the humans generally win.

Yosdis (2001) points out that there are growing calls for the culling of top predators (particularly marine mammals) in order to increase food production, and such thinking has been shifting the focus of some organizations such as the International Whaling Commission (IWC) from a single- to a multi-species perspective. Yosdis (2001) makes the point that if top predators do indeed compete with fisheries, then it is equally arguable that fisheries compete with top predators, and in fact the latter is considerably more likely given the powerful technology, the abundance of alternative resources and the lack or weakness of ecological feedback mechanisms.²⁴ However a much more significant point is that given the unpredictable nature of trophic interactions, there is rarely enough information available to determine the magnitude or even the direction of a response to a prey species of a predator cull. The example given is one in which top predators (say a pinniped population) eat both a finfish species targeted by a fishery and another finfish species which is a predator of that targeted by the fishery. In response to a cull, predation pressure is released both on the species targeted by the fishery, as well as another major predator on that target species, and the subsequent response is a combination of the effects of both of these changes propagating through the food web over time, with the potential to be positive or negative depending upon the nature of the interactions. For example, Punt and Butterworth (1995) predicted that the cull of Cape fur seals in the Benguela Current could have neutral to detrimental effects on the Cape hake fisheries in the region, based on the potential for tightly coupled interactions between the two species of hake (one of which was a predator on another) in that ecosystem.

Precisely because top-down and bottom-up community behavior is so complex, the predictability of ecosystem consequences resulting from fishing activities is very low. As Hollowed et al. (2000) review, there is an increasing trend towards multispecies or ecosystem models to address some of these interactions (key results being better estimates of natural mortality and

²⁴ A point also made in the groundfish fisheries FMP biological opinion, which points out that “Sea lions or other ecosystem consumers, do not have the technological advantages of fishing fleets or the ability to change strategies, and have limited physiological reserves to cope with declining availability... When biomass reaches a threshold, predators are no longer able to successfully forage for that prey, even if considerable biomass remains in the system” (page 207, NMFS 2000).

recruitment), but their current sophistication and predictability is considered to be low. This is due both to the simplicity of model assumptions (although these are generally quite similar to those of single species models) and the lack of adequate data or knowledge to parameterize such models (the major shortcoming of any attempt to model trophic dynamics in ecosystems, as even in intensively studied ecosystems many abundance estimates and key population parameters are unknown). Most modelers acknowledge that uncertainty tends to increase with multispecies models; consequently the potential error surrounding parameters, results and consequent insights from ecosystem models is tremendous. However it is equally clear that these models are evolving rapidly as the need for understanding complex interactions becomes increasingly apparent. What is most critical is the recognition that exploited fish populations sit within complex food webs, and that removals from fishing have the potential to result in undesirable consequences to target and dependent species as well as entire ecosystems.

3.5 Other Impacts to Marine Ecosystems

These examples illustrate the dramatic increase in the challenges of considering error, evolution, demography, environmental and ecosystem interactions beyond simply single-species perspectives; however they still exclude a tremendously wide range of fishery and non-fishery related impacts that can and do have consequences to marine populations and ecosystems. Pollution, vessel disturbances and the effects of fishing gear on habitat are just a few additional fisheries impacts. Non-fisheries impacts include the effects of habitat degradation and loss, pollution, water diversion in estuaries and coastal areas, nutrient enrichment and eutrophication, invasive species and global climate change just to name a very few (NRC 1998). Generally, external stressors tend to be more important near major population centers and for populations with estuarine or nearshore dependent life history stages, consequently most populations and ecosystems under the jurisdiction of the North Pacific Council are subject to relatively minimal non-fishery related human impacts. However populations are not immune to such problems, as impacts such as contaminant loading (PCBs and DDT) have become substantial for some populations (typically seabirds and marine mammals), and certainly global change has the potential to drive dramatic impacts to these Northeast Pacific marine resources.

The interactions between global change and intensive exploitation will have tremendous consequences to the marine environment, particularly with regard to the challenge of attributing changes in abundance to their true causes. Evidence already suggests that high latitude and polar ecosystems will be subject to the greatest disturbances and impacts in terms of loss of sea ice, warming of ocean temperatures, alteration of seasonal and interannual modes of variability and changes in ocean currents and other physical processes, indeed some evidence suggests that massive declines in Arctic sea-ice extent have already occurred.²⁵ Such changes in physical forcing should be expected to have dramatic consequences to high latitude biota and ecosystems (IPCC 2001, Scavia et al. 2002), as ice edges have been demonstrated to be regions of intense primary and secondary productivity (Niebauer 1991, Wheeler et al. 1996) as well as critical habitat for many marine mammals (Tynan and DeMaster 1997, Stirling 1997). Already, anecdotal evidence suggests that impacts to marine ecosystems and top level predators have begun, in particular as evidenced by the changing availability of many marine mammals to native hunters in Polar regions (Weeler and Anderson 1998, Huntington 2000). While the consequences of ongoing and future changes are highly uncertain, Mantua and Mote (2002) offer some simple advice for anyone involved with resource science, management or policy, which is to recognize that “environmental uncertainty will always be a fundamental component of nature... While future climate change will not change this basic truth, it will likely bring heretofore unknown environmental changes and related impacts.” They also suggest that contemporary climate change scenarios often suggest widely varying regional impacts, and consequently are not likely to provide deterministic advice regarding likely consequences to either marine or terrestrial ecosystems.

Moreover, the effects of exploitation and environmental change can be synergistic; that is, environmental changes that result in a reduction in the productivity of a marine resource can result in the decline or collapse of a population under levels of exploitation that might be sustainable under favorable environmental conditions. For example, coral reef ecosystems appear to be capable of withstanding significant chronic or acute stresses, but rarely both.

²⁵ Rothrock et al. (1999) estimate that Arctic sea ice has been decreasing by as much as 15% by volume in the Arctic over the past four decades, and noted that record low levels of sea ice were observed in the Bering and Chukchi seas during an extremely warm 1998, Stabeno et al. (2001) provide a more detailed account of the associated impacts with physical and biological processes associated with this particular event. More general discussion of the impacts of climate on physical forcing and marine ecosystems can be found in the Intergovernmental Panel on Climate Change (2001) reports as well as Boesch et al. (2000).

Hughes and Connell (1999) demonstrated that reefs damaged by acute episodic events (such as dramatic short term sea-surface temperature spikes, as observed during the 1997-98 El Nino event) will recover if other environmental factors remain generally favorable, and coral communities may persist under chronic sub-optimal conditions (such as intensive fishing pressure or eutrophication) in the absence of acute stresses; but once a chronically stressed reef is damaged, recovery is unlikely. Thus the interaction between external stressors such as global change, habitat alteration and nutrient enrichment may interact with the direct and indirect consequences of fishing, resulting in marine ecosystems that are increasingly vulnerable to undesirable ecological changes.

4 The Application of $F_{40\%}$ in the North Pacific Fisheries

Witherell et al. (2000) suggest that the groundfish fisheries under the jurisdiction of the North Pacific Fishery Management Council are managed “consistent with a precautionary approach and ecosystem-based management, and have resulted in sustainable fisheries.” They support this claim with a comprehensive summary of management practices that are indeed consistent with a precautionary approach, including the precautionary application of target and limit fishing mortality reference points under the tier system, the current moratorium on the development of new fisheries for forage species, a cap on the total annual allowable catches in the Eastern Bering Sea (of 2 million metric tons), the wide-spread application of closed areas to protect crab and Steller sea lion foraging habitat, the implementation of widespread observer coverage and high data quality and availability. However the claim is not necessarily consistent with the Bering Sea/Aleutian Islands Groundfish Fishery Management Plan (NPFMC 2002a), which states that with regard to the ecological impacts of fishing “it is not possible to predict the long-term effect on the ecosystem of the current, single species management strategies (as opposed to the integrated ecosystem method) or of subtle environmental changes.” The plan goes on to state that because reliable means of developing more complex ecosystem models to provide management advice continue to be lacking, existing models and theories used to manage fisheries resources, as tempered by their underlying assumptions, provide a useful context for making management decisions.

4.1 North Pacific reference points from a single-species perspective

The current guidelines for the implementation of National Standard 1 of the Magnuson Act state that “In general, Councils should adopt a precautionary approach to the specification of OY”, and the nature of the appropriate measures for applying a precautionary approach have been detailed in the Technical Guidance for National Standard 1 (Restrepo et al. 1999). Generally, the required elements of the precautionary approach have focused on the definition of limits or thresholds for fishing mortality rates, where MSY or a reasonable proxy thereof is the “minimum standard” for the maximum fishing mortality threshold (MFMT), and for biomass levels, in which a minimum stock size threshold (MSST) is set as a threshold for biomass levels. Both of

these thresholds are the standards against which stock status is assessed to determine whether overfishing is occurring ($F > MFMT$) or whether a stock is in an overfished state ($B < MSST$). These limits are more conservative than target fishing mortality rates and biomass levels (targets are associated with achieving OY) that must by definition be “safely below” the limits, as stated in the technical implementation “Setting OY at its limit (MSY in the Magnuson-Stevens Act) would not normally be precautionary because there could be a high probability of exceeding the limit year after year. Under the precautionary approach, the target should be set below the limit taking uncertainty and other management objectives into consideration” (Restrepo et al. 1999). Although Councils have considerable latitude in defining both targets, limits and appropriate proxies for MSY, the default control rule provided as guidance would set the target at 25% of the limit, suggesting that this level of precaution is appropriate for most scenarios.

The North Pacific Fishery Management Council approach to setting target and limit reference points is consistent with the intent of the National Standard Guidelines, as it should be given that this approach was used by NMFS as a model for implementing target and limits and the corresponding control rules. Currently, the North Pacific Council applies a 6-tier management system, which operates on a sliding scale determined by the amount of information available for each target stock or stock complex, such that greater uncertainty is presumably associated with lower target and limit fishing mortality rates (Witherell and Ianelli 1997). Stocks in tier 1 and 2 are managed with MSY as the limit reference points, although only one stock (eastern Bering Sea pollock) is currently thought to have sufficient information to determine MSY reliably. Even for this stock, the questionable dependability of the model has often led to the estimation of target fishing mortality rates using the $F_{40\%}$ proxy rather than F_{MSY} (Ianelli et al. 2001). Given that a key theoretical basis for management by proxy reference points is that they are consistent over a fairly wide range of stock recruit relationships, the lack of solid evidence for clear stock-recruitment relationships of any sort in Northeast Pacific fisheries (as demonstrated by this solitary member of tier 1) should be disconcerting.

For the North Pacific Council, stocks in tiers 3 and 4 are those which are managed based on the $F_{40\%}$ proxy, which include most of the fisheries of significance by both value and volume aside from EBS pollock. Management by these proxies requires reliable point estimates of biomass (B) and proxies for OFL and MSY values ($F_{35\%}$ and $F_{40\%}$ respectively), which in turn require

adequate data on maturity, growth and natural mortality rates. More importantly, because a stock-recruit relationship is not known for these stocks, estimates of B_0 (by definition necessary to define $B_{40\%}$ and consequently $F_{40\%}$) are based on the average recruitment over the available time series and the estimated natural mortality rate; neither of which can be known with any reasonable precision. Under scenarios of environmentally driven changes in recruitment trends, the average estimated recruitment will tend to vary over time with consequent variations in point estimates of $B_{40\%}$ and other reference points. Additionally, if there is a stock-recruit relationship for a given stock and recruitment has declined with stock abundance (even if a stock is at levels above the target biomass levels), B_0 will be underestimated as the mean recruitment would not reflect the mean recruitment in an unfished condition. The concept of a B_0 itself is one of an equilibrium condition, and consequently has significant conceptual flaws as it may both over- and under-estimate the “unfished biomass levels” of any particular stock in systems characterized by long-term environmental variability, as the EBS and GOA seem to be.

Despite this, the current application of the $F_{40\%}$ target harvest rate in the North Pacific satisfies the criteria for implementation of the precautionary approach based on the interpretation of the technical guidelines from implementing National Standard 1 (Restrepo et al. 1999). All of the tiers place a buffer between overfishing limits (OFLs) and allowed biological catches (ABCs) which satisfies the first characteristic of a precautionary approach (NMFS 2001). Tiers 1-3 also satisfy the second characteristic by decreasing fishing mortality rates for stocks that fall below the MSY or MSY proxy level²⁶ and tier 1 satisfies the third characteristic of a precautionary approach by reducing the target fishing mortality rate in direct relation to the level of uncertainty regarding the stock’s productive capacity, such that greater uncertainty leads to a lower target fishing mortality rate. Tiers 1 through 4 also specify maximum fishing mortality thresholds (MFMTs) that are fishing mortality rates that result in overfishing, and minimum stock size thresholds (MSSTs) that define a stock as overfished.

²⁶ In addition to the tiers themselves, there are sub-tier designations a,b and c in tiers 1-3 which correspond to the estimated abundance of the stock relative to the target biomass level. Stocks in subtier a have biomass levels higher than or equal to the target (B_{MSY} or B_{40}), and harvest rates can be set as high as F_{MSY} or $F_{40\%}$. Stocks in subtier b are below the target biomass level and harvest rates are buffered below the target according to guidelines set by default or by the SSC, while stocks in subtier c are in an overfished or depleted condition and no harvest is allowed. See Council SAFE documents, NPFMC 2001a and 2001b, for clarification of the tiers and the exact formulation of these harvest policies.

In Tier 5, available estimates of biomass and natural mortality are used to set overfishing level (OFL) equal to M and target fishing mortality rates (F_{ABC}) to $0.75M$. In tier 6, where even reasonable estimates of M are unavailable, the OFL is set at the average catch over a period of time (usually 1978 through 1995) and the ABC is set at less than or equal to 75% of this average catch. Although Witherell et al. (2000) suggest that management of lower tier (information poor) stocks is conservative because “Both the $F_{40\%}$ and $0.75 M$ rates are considered conservative harvest rates for most groundfish stocks”, this review has cited multiple examples where such reference points may in fact *not* be conservative for many life history types, which include many of the data poor species that are targets of BS/AI and GOA fisheries such as rockfish (*Sebastes* and *Sebastes* spp.) and elasmobranchs, which have been often shown to have low compensation. Walters and Parma (1996) expressed considerable concern about $F \approx M$ harvest rates for long-lived species in particular, suggesting instead that a prudent approach would constrain harvest rates below $0.5 M$. They also suggest that the burden of proof should be placed “on whoever advocates a higher rate to demonstrate that it is sustainable (by substantial direct analysis of historical stock-recruit data).” Part of their rationale for this approach is that the consequent reduction in yield for long-lived species is relatively minor, with concurrently greater protection for the integrity of the stock. As discussed in section 2.2, Dorn (2002) suggested that for most West Coast rockfish, $F_{50\%}$ would be a reasonable risk-neutral proxy of F_{MSY} , noting that a truly risk adverse strategy could justify substantially lower ($F_{55\%}$ to $F_{60\%}$) harvest rates. The Pacific Fishery Management Council has since implemented an $F_{50\%}$ proxy for F_{MSY} for all *Sebastes* and *Sebastes* stocks. For these and the many other reasons cited throughout this review, it is overly optimistic to assume that either $F = 0.75M$ or $F_{40\%}$ is conservative across life history types; especially given that for many stocks it is not possible to assess unfished biomass levels and consequently the potential for being in or approaching an overfished condition.

There could reason to suspect $F_{40\%}$ might not be sustainable for some more “typical” groundfish as well. The observation by Mace and Sissenwine (1993) that many small gadids have high replacement %SPR values could suggest that pollock are more vulnerable to overfishing under aggressive harvest strategies than currently believed, in part because life histories may be closer to those of forage species than that of larger piscivores such as Pacific (or Atlantic) cod. Certainly the central role that juvenile and adult pollock play in food webs throughout the Bering

Sea and Gulf of Alaska might support such a conclusion. The observation by Hutchings (2000, 2001) that many stocks (including a disproportionate number of gadids) have not shown strong signs of recovery following high levels of depletion further indicates that some stocks may not be as robust as the theoretical populations for which these reference points were developed. Consequently, management for those stocks with significant downward trajectories may require greater conservatism than is inferred from straightforward application of the current harvest policy.

Hollowed et al. (2001) suggest that for some dynamic stocks, a substantial proportion of the variability observed in biomass, recruitment or productivity is independent of factors such as habitat, carrying capacity or trophic interactions; they refer to this as “Pure temporal variation” (PTV). Although one interpretation of this affect may suggest that the role of fisheries is minimal with respect to climate-ocean interactions, it may also be that the adaptive mechanism for coping with such changes is incompatible with constant harvest strategies based on equilibrium assumptions. In fact, the critical management measures for such species may not necessarily be what is done during years of good recruitment and high abundance, but rather how the resource is managed during periods of poor recruitment and low abundance. Sustained mortality in excess of that which might be expected without fishing could inhibit the ability of stocks with such life history strategies to weather prolonged poor environmental conditions, particularly for species that play a central role in food webs (Rice 2001). Alternative management strategies, perhaps akin to those adopted for California sardine (described in section 2.2), could be more appropriate under such scenarios.

Referring back to the genesis of %SPR based reference points in section 1.2.4, recall that while $F_{40\%}$ is one of the more conservative proxies for MSY, it was, in fact, intended to be a proxy for MSY that was more appropriate than $F_{35\%}$ for stocks with variable recruitment (Clark 1993). This also suggests that the precautionary reduction from F_{MSY} as a limit to $F_{40\%}$ as a target is relatively small, if it exists at all. However few of the stocks managed by the North Pacific Council are actually harvested at levels approaching the ABCs, as TACs by definition must be set at or below the ABC and most are set below, and often considerably below for a wide range of reasons. Furthermore, actual catches are often considerably less than allowable catches, for a variety of ecological, managerial and economic reasons.

Table 4.1 provides a summary of many (albeit far from all) of the key stocks managed by the North Pacific Council in the Gulf of Alaska (GOA), Aleutian Islands (AI) and Eastern Bering Sea (EBS), from data made available in NPFMC 2001a and 2001b and the individual stock assessments themselves. For each stock, the table includes the corresponding tier that the stock is managed under, the current spawning stock size (where available) relative to the equilibrium level, the most recent (total adult) biomass estimates for 2002, the recommended ABC for 2001, the estimated catch through November 15th in 2001, and the percentage of allowable catch that was actually caught (to that date).

Stock	Tier	SSB _{obs} /SSB ₀	2002 biomass	2001 ABC	2001 catch	catch/ABC
EBS Pollock	1a	45%	9,800,000	1,842,000	1,381,598	0.75
AI Pollock	5	n/a	106,000	23,800	819	0.03
Bogoslof Pollock	5	n/a	323,000	45,200	29	0.00
BSAI Pacific Cod	3b	39%	1,540,000	188,000	154,991	0.82
BSAI Yellowfin sole	3a	48%	1,597,000	176,000	54,340	0.31
Greenland turbot	3a	66%	208,000	8,400	4,210	0.50
BSAI Arrowtooth	3a	94%	671,000	117,000	13,464	0.12
BSAI Rock sole	3a	98%	1,850,000	228,000	28,882	0.13
BSAI Flathead sole	3a	74%	695,000	84,000	40,000	0.48
BSAI Atka mackerel	3b	38%	439,700	58,700	56,521	0.96
GOA Pollock	3b	26%	726,600	99,350	70,416	0.71
GOA Pacific Cod	3b	39%	428,000	67,800	41,085	0.61
GOA Rex sole	5	n/a	71,326	9,440	2,939	0.31
BSAI+GOA Sablefish	3b	35%	193,000	17,300	13,922	0.80
GOA Pacific Ocean Perch	3a	43%	293,240	13,510	11,028	0.82
GOA shortraker/rougheye	4/5	n/a	66,830	1,730	1,925	1.11

Although the table excludes a large number of stocks, several factors are quickly apparent. The most significant is that very few stocks are actually harvested at rates approaching those based on the MSY or MSY proxy for the ABC. There are a number of explanations for this; the most obvious for some stocks, Arrowtooth flounder being the most conspicuous amongst them, is simply a lack of significant commercial value. The landings for other stocks, such as rock sole and yellowfin sole in the Bering Sea, are often constrained by high bycatch rates, which close the fisheries as target levels of prohibited species are attained.²⁷ For Bogoslof and Aleutian Island

²⁷ Although the bycatch of prohibited species, typically halibut, are the key constraints on these fisheries, they also have some of the highest rates of non-retention in the Northeast Pacific. For example, the Rock Sole fishery has discard more rock sole than have been retained since 1987, with recent retention rates generally ranging between 33 and 45% of the total catch (Wilderbuer and Walters 2001).

pollock, historically high catches that apparently resulted in substantial localized depletions, and consequent concerns over the local significance of pollock as a prey resource for Steller sea lions, have resulted in closures to directed fishing. The Bogoslof closure has been in place since 1992 and the Aleutians closure since 1998. The difficulties associated with identifying stock structure, and consequently avoiding localized depletion of distinct subpopulations have also been acknowledged; Macklin (1999) cites evidence for several distinct spawning aggregations in the AI and EBS region, and Ianelli et al. (2001) suggest that the stock identification issue is not yet resolved.

The explanation for other species often includes the consideration of additional uncertainty by stock assessment authors and the plan team, which result in precautionary adjustments to the estimates of either the ABC or the TAC for a given stock. For example, both survey and assessment results suggest a considerable long-term decline in GOA pollock over the past two decades, with recent surveys suggesting potentially dramatic declines (15 to 65%) over just the last two years. The most recent assessment estimates spawning stock at 26% of the equilibrium, a level approaching an overfished condition. Noting that the effective buffer between the ABC and the OFL decreased at low stock sizes, the assessment authors (Dorn et al. 2001) developed an alternative harvest rule that would maintain a constant buffer between the ABC and the OFL at all stock sizes. Similarly, past assessments for BSAI Pacific Cod had expressed concern over estimates of natural mortality (M) and catchability (q) and consequently used Bayesian methods to address uncertainties around these parameters. The results of this analysis justified a reduction from the recommended fishing mortality rates to approximately 87% of $F_{40\%}$, a percentage now standardized in current assessments based on the past analysis (Thompson and Dorn 2001).²⁸ Finally, in assessing Atka mackerel stocks, factors related to high survey variability and the life history characteristics of the species (which include massive spawning aggregations, low fecundity and some behavior patterns) have been cited as a complicating factor in generating reliable reference points. The authors of past assessments used additional ways of characterizing the uncertainty around survey estimates, which justified lowering target harvest

²⁸ Additional concerns cited by the BSAI Plan Team are related to the dome-shaped nature of the model-estimated selectivity curve, which implies a greater biomass of older fish outside of the survey area (and consequently a greater biomass of the stock in general) which there appears to be no evidence for (NPFMC 2001a). Related to this concern were concerns over the age composition of the adult spawning stock expressed by the Scientific and Statistical Committee (cited in Thompson and Dorn 2001) in which the demonstrated importance of age structure of Atlantic cod was cited.

rates from $F_{40\%}$ to approximately $F_{52\%}$. Although the SSC did not endorse the exact procedures for reducing the ABC, they “recognized the $F_{40\%}$ value to be clearly too high” (Lowe et al. 2001) and have consequently endorsed $F_{52\%}$ as an appropriate harvest strategy for this stock.

Although additional caution is taken in setting fishing mortality rates for other stocks, these examples set a pattern in which stocks which have been the focus of some of the most intensive fisheries (as estimated by the proportion of the TAC that has actually been landed) have also been subject to unique estimations of additional uncertainties that warrant additional reductions in target fishing mortality rates from $F_{40\%}$. This is consistent with the approach delineated by the Council, which suggested that $F_{40\%}$ was an upper bound for F , not to be simply an across the board target, yet this does speak to the potential inappropriateness of $F_{40\%}$ as a target more generally. In other words, $F_{40\%}$ has consistently been judged as inadequate by stock assessment authors, the SSC and the Council as a precautionary harvest rate. These measures that have been build into ABC decisions are consistent with greater precaution, and fisheries management by the North Pacific Council can and should be considered precautionary from a single species perspective as delineated by the National Standard guidelines and technical guidance. However, there may be a lack of precaution associated with the guidelines (and subsequent implementation) themselves, as evidenced by the wide range of opportunities for error, the increasingly observed low productivity of many stocks, the potential consequences of impacts such as evolutionary and demographic shifts, the potential for past and current depletion of localized stock structure, and obviously the trophic and habitat related impacts.

4.2 North Pacific reference points from multi-species and ecosystem perspectives

As Mangel et al. (2000) state “Single-species management is based on the assumption that stocks can be viewed out of the context of their role in the ecosystem, that density dependence is the main regulating factor in population dynamics, and that if one simply knows enough about the vital information of the stock, then it is possible to fully control the trajectory of the stock. This is true whether one uses surplus production models, dynamic pool models, stock recruitment models, VPA or other more sophisticated tools.” While considerable ecological and ecosystem research has been undertaken to better understand trophic interactions in the Eastern Bering Sea

and Gulf of Alaska²⁹, such interactions are rarely considered in contemporary stock assessment advice, which remain based in a single-species paradigm. More significantly, there is no clear consensus on what would actually constitute precautionary harvest policies or rates from a multispecies or ecosystem perspective, although there seems to be some consensus that an ecosystem-based management approach would include less aggressive harvest strategies and greater buffers to account for additional sources of uncertainty.

In the North Pacific there are a great many unknown interactions and potential consequences related to both past and present management activities, as well as patterns of climate variability, that merit a great deal of concern. Macklin et al. (2002), Hunt and Stabeno (2002) and Connors et al. (2002) include comprehensive summaries of the evidence for physical and consequent biological changes in the Bering Sea in particular over the past 40 years, and Bailey (2000) reviews similar evidence in the Gulf of Alaska. These observations severely complicate any effort to attribute population, community or ecosystem changes with causal agents. Although strong arguments could be made that large scale ecological changes have resulted from either climate variability and/or change, from direct and/or indirect consequences of fishing activities, or (the most likely explanation) some combination of these two forces; conclusive arguments for any of these explanations have proven elusive.

The NRC (1996), Orensanz et al. (1998) and Francis et al. (1999) point out that the Bering Sea, Aleutian Islands and Gulf of Alaska ecosystems are far from pristine systems. Instead, these are ecosystems in which populations and communities have gone through substantial and often changes; including the first marine mammal extinction (the Steller sea cow), the severe depletion, recovery and recent downward trajectory of sea otters and many other marine mammals (Estes et al. 1998), and the depletion of many shellfish stocks, some of which have yet to recover (Orensanz et al. 1998). It has long been suggested that heavy commercial harvests of

²⁹ There is a wide range of ecosystem research and modeling done in these ecosystems, for example Livingston (1993), Livingston and Methot (1998) and Hollowed et al. (2000) developed means to take major sources of predation mortality into account when estimating natural mortality rates for pollock; some of their results suggested that natural mortality may be substantially underestimated under some conditions. Francis et al. (1999) also summarize much earlier work on applied ecosystem modeling in the region, and discuss the role of multi-species and ecosystem models more generally to the Bering Sea ecosystem. Other efforts include multispecies VPA models (Livingston and Jurado Molina 2000) and ecosystem models (Trites et al. 1999, Aydin et al. 2002) in this region. Although models and results have improved the understanding of trophic interactions and ecosystem structure, and have been increasingly discussed as valuable tools for informing managers, they have not yet been used for explicitly guiding management.

long-lived species (particularly marine mammals) between 1955 and 1975 could have led to a sequence of cascading events (such as increased availability of zooplankton forage and reduced juvenile mortality) that allowed for dramatic increases in many groundfish populations thought to have occurred since the mid 1970s. Yet any such changes would have also occurred in tandem with large-scale changes in climate conditions that are widely acknowledged to have occurred throughout the North Pacific since the mid 1970s.

The question of whether effective single species management equates to successful multi-species management was made by the NRC Committee on the Bering Sea Ecosystem (1996) which recognized “fundamental conflicts between the usual goals of maximizing yields in marine fisheries management and the goals of the Endangered Species Act, Marine Mammal Protection Act, and the National Environmental Policy Act”. The NRC statement was focused on the (then) lack of consideration in groundfish management for the foraging requirements of Steller sea lions and other marine mammals and seabirds in the Bering Sea and Gulf of Alaska. Since that time, excruciatingly complex management efforts have resulted in increasing control over fishing activities in space and time, intended to reduce conflicts between fisheries and other species. Such efforts include more conservative control rules for setting target fishing mortality rates for key Steller sea lion prey species, a ban on new fisheries for “forage” species, a cap on total allowable catches in the Eastern Bering Sea and most significantly a large-scale spatial and temporal management measures to address Steller sea lion foraging needs.

While these measures have not necessarily resulted in a substantial change in the overall yield-maximizing harvest rate strategies for most stocks in the region (although they could constrain future fisheries), they have resulted in large scale research and management efforts to address the very real temporal and spatial nature of many of the fisheries, in an attempt to reduce the extent to which fisheries compete directly with predators for prey. The bulk of these efforts have focused on observed and potential interactions between sea lions and groundfish fisheries throughout their range, and while the level of research and detail is far too great to address here some highlights are relevant to this discussion. The Biological Opinion for the groundfish FMP (NMFS 2000) raises a very large number of relevant known and unknown factors that suggest that there may indeed be very real consequences to Steller sea lions in particular, that result from the $F_{40\%}$ harvest rate strategy.

As mentioned previously, trophic interactions are not formally considered in stock assessment advice. Instead, “other species prey requirements for each exploited groundfish species are considered only to the extent to which they are captured within the natural mortality rate parameter, M , one of the most difficult parameters of a fish population to measure” (NMFS 2001). Figure 4.1 shows a simple example (from NMFS 2000) of what the consequences of $F_{40\%}$ are to the key prey species of Steller sea lions in the Gulf of Alaska, estimated very simply by running model estimated recruitments forward in time without fishing mortality (black) as compared to the contemporary model estimates that include observed fishing mortality (gray). While it is clear that even without fishing, some biomass levels would not be expected to be close to their peak levels of the early 1990s (in other words, some stocks would be expected to be at levels significantly below what is defined as B_0 even in the absence of fishing based on recruitment trends), it is equally clear that the consequence of fishing to some stocks has been proportionally greater in recent years as stocks have declined to levels both approaching and decreasing below $B_{40\%}$.

Admitting that a substantial amount of conjecture was involved, the NMFS determined that fishing activities that caused stocks of major forage species to drop below 40% of B_0 could result in a take of ESA listed Steller sea lions. Most of the measures implemented to avoid this take relate to the complex suite of spatial and temporal management measures that have dominated much of the discussion regarding this issue, but harvest rates themselves for key forage species are determined by a global control rule implemented to prevent such declines. The global control rule reduces fishing mortality from target levels to 0 as stock size falls between 40% and 20% of B_0 , with the objective of preventing the stock from falling below 20% of B_0 . Yet given the combination of error surrounding both estimates of B_0 and estimates of current biomass levels, as well as both short and long term unpredictability in future recruitment levels and trends, this strategy still poses a substantial risk of allowing prey biomass levels to decline beyond $B_{20\%}$.

Larkin (1996) suggests that while an ecosystem-based approach to fisheries management distills down to a question of distinguishing the impacts of fishing from those of climate, “One of the morals is to ease up on fishing when environmental conditions are unfavorable.” Although the

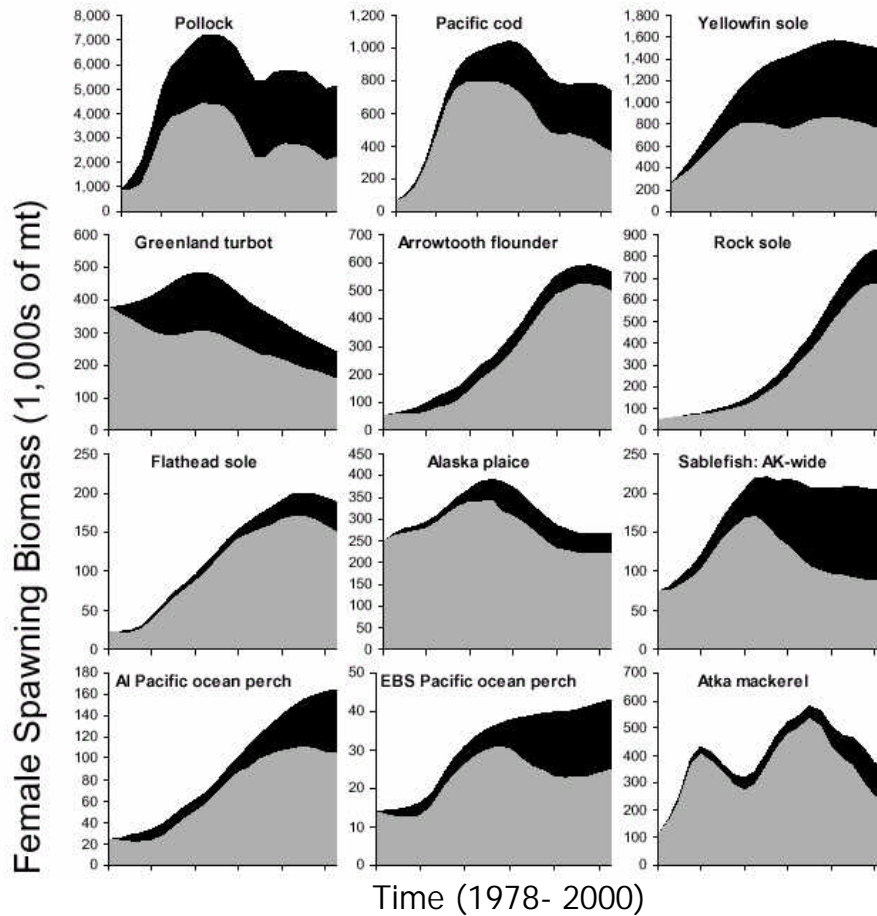


Figure 4.1: From NMFS (2000), observed and potential biomass levels of key species in the BS/AI based on forward projection of observed recruitments between 1978 and 2000.

control rules for setting fishing mortality rates do this, and the global control rule implemented in response to the BiOp is even more restrictive, there is no conclusive evidence to suggest that such reductions are sufficient to sustain the foraging requirement of predators during periods when declines may be intensified by ongoing fisheries. Because the foraging requirements of other species are considered only to the extent to which they are captured within model estimates of natural mortality (M), the expected differences between fished and unfished trends seen in these figures are proportional to the flux of biomass (and thus the difference in the flux of biomass) from these stocks to their predators. Whether these changes are within the formerly natural range of variability for these stocks, and whether the consequences of these declines impact Steller sea lions or other organisms, is an unknown, and perhaps unanswerable, question.

The question of whether the application of $F_{40\%}$ in these fisheries, or the concept and principle of $F_{40\%}$ in general, leads to jeopardy for Steller sea lions (or any other animal) is certainly not one to be decided here. Given the multiple interactions between the substantial amount of uncertainty and error that we are aware of, on top of a great deal of uncertainty regarding ecosystem processes, stability, interactions with climate and trophic relationships, deciphering what factors have contributed the most to the decline of the species is a difficult task. However it does appear clear that the strengths of $F_{40\%}$ as a management target are based on the merits of this approach from the perspective of the sustainability of the stock itself, not from the sustainability of its predators. Certainly there seems to be no empirical evidence that $F_{40\%}$ is precautionary from the perspective of interspecific interactions.

4.3 North Pacific Fisheries and $F_{40\%}$ from an ecosystem perspective

Increasingly, an ecosystem-based approach fisheries management is being touted as a necessary supplement to current single-species approaches throughout both the U.S. and the world (Botsford et al. 1997, EPAP 1999, Mangel et al. 2000, Pauly et al. 2002), although as Larkin (1996) suggests “these are not new ideas.” Essentially, an ecosystem-based management approach involves a more holistic view of managing resources in the context of their environment, for marine fisheries this must take into greater consideration the interactions between climatic and oceanographic processes, the connections and interactions between fished and unfished populations in the ecosystem and the role of humans as both predators and competitors in such ecosystems. The latter point is especially important, as it has become increasingly clear that the linkage between humans and resources need to be more balanced, an objective made difficult by the mismatch between societal and ecological feedbacks. As Rice (2001) explains, “Fisheries have a trait not shared with natural predators. They can vary their maximum capacity to consume prey on nearly annual time scales, rather than time scales of several generations of their prey. This means fisheries function very differently from the type of predators on which predator-prey population dynamics models are based.”

The Congressionally requested report by the Ecosystem Principles Advisory Panel (EPAP 1999) provides a framework for moving towards an ecosystem-based approach to fisheries management, although other sets of principles and guidelines exist (see Mangel et al. 2000 for a

review). The essence of the EPAP report is recognition of ecosystem properties and principles, including:

- The ability to predict ecosystem behavior is limited
- Ecosystems have real thresholds and limits which, when exceeded, can effect major system restructuring
- Once thresholds and limits have been exceeded, changes can be irreversible
- Diversity is important to ecosystem functioning
- Multiple scales interact within and among ecosystems
- Components of ecosystems are linked
- Ecosystem boundaries are open
- Ecosystem change with time

The panel suggested a set of basic policies as means towards achieving these objectives, including changing the burden of proof, applying the precautionary principle, purchasing “insurance” against unforeseen, adverse ecosystem impacts, and learning from management experiences. The vehicle for implementing these policies was envisioned as a “Fisheries Ecosystem Plan” (FEP) which would serve as an umbrella document describing the structure and function of the ecosystems being managed (including the food web), describe habitat needs for all life stages of organisms (an objective being addressed under the Essential Fish Habitat provisions of the Sustainable Fisheries Act) account for total removals and impacts from fishing, describe how uncertainty is characterized and buffered against, develop indices of ecosystem health, describe long term monitoring data and how they are used, and assess other human activities with consequences to the ecosystem. The ultimate objectives would be to increase the awareness of managers and stakeholders of the effects that their decisions have, recognizing that all management decisions have impacts on an ecosystem regardless of how they might be characterized.

There have indeed been very real accomplishments and advances by the North Pacific Council in moving towards greater integration and implementation of ecosystem considerations in managing resources under their jurisdiction; in fact this Council is likely better prepared than any other for fully implementing an ecosystem-based approach to fisheries management in the future. In addition to the measures described earlier, the Council has established an ecosystems committee, included an ecosystem considerations chapter in the Stock Assessment and Fishery Evaluation (SAFE) document, has been at the forefront of implementing measures to protect habitat from gear impacts as well as is supported by tremendous financial and human resources

in ecosystem research. Yet this neither confirms that current practices are wholly sustainable in the long term nor that substantial long-term cumulative consequences to the ecosystem have not already resulted from earlier actions (or activities outside of Council jurisdiction).

The question of whether the sum of sound single-species management efforts results in successful ecosystem-based management is an unanswered, and perhaps unanswerable one, as the risk of stock depletion from overfishing and the potential consequences to dependent species and/or ecosystem integrity from overfishing are very different considerations. Even under a scenario in which all of the legal mandates of the Magnuson Act, the Endangered Species Act, the Marine Mammal Protection Act and the National Environmental Policy Act were fulfilled, the lack of consensus regarding what an ecosystem-based approach to fisheries management would actually look like complicates any accurate assessment. Consequently, our collective inability to define what is truly precautionary from an ecosystem perspective should prevent us from waving a checkered flag at sustainability; we do not truly know if we are there yet and given considerable uncertainties surrounding the potential causes of species declines we should suspect that we might not be. Mace (2001) suggested that while recent changes in fisheries management in the U.S. have focused on reducing fishing mortality rates to below those at MSY (or proxies thereof), as the North Pacific Council has done, even greater reductions will be necessary if it is decided that fisheries are to be managed from an ecosystem perspective. The CCMLAR approach towards species considered as forage, albeit for a very unique situation, raises the bar considerably for what approaches may be truly precautionary and sustainable from an ecosystem perspective.

Mace (2001) also suggests that the current fisheries management record to date cannot be used as evidence that single-species approaches do not work, as management targets have rarely been achieved on paper. This is precisely why the outcome of various crises in the North Pacific will be critically important in assessing the efficacy of fisheries management trends in the future, for as opposed to most other U.S. managed ecosystems, implementation of management advice based on high quality scientific assessments has been largely successful in the Bering Sea and Gulf of Alaska. Currently no groundfish stocks are thought to be overfished (although several are below target levels), and relatively few stocks overall (several crustacean populations being the exceptions) are depleted as a result of historical overexploitation. Perhaps more importantly,

implementation of contemporary management measures is highly successful. Yet despite these successes, there have been tremendous shifts in community structure, undesirable declines in key populations of top level predators, and complex interactions with highly dynamic physical processes. This could suggest that the ecosystems under the jurisdiction of the North Pacific Council are to a large extent test cases that may very well determine the extent to which successful implementation of the current 'precautionary' paradigm is truly sustainable over the long term.

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