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Review

A review of harvest policies: Understanding relative performance of control rules

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ABSTRACT

Harvest policies use control rules and associated policy parameters to dictate how fishing mortality or catch and yield levels are determined, and are necessary for rational management. Common control rules include constant catch, constant fishing mortality rate, constant escapement, or a few variations of these. The "best" among these control rules for meeting common fishery objectives (e.g., maximizing yield) is a source of controversy in the literature, and results are seemingly contradictory. To compare the ability of control rules to meet widely used fishery objectives and identify potential causes for these apparently contradictory results, we did a detailed review of relevant literature. The relative performance of control rules at meeting common fishery objectives is affected by: whether uncertainty in estimated stock sizes is included in analyses, whether the maximum recruitment level (e.g., the asymptote of a Beverton–Holt stock–recruit function) is varied in an autocorrelated fashion over time, fishery objectives, and the amount of compensation in the stock–recruit relationship. Few studies have compared control rules using optimal parameters (e.g., those that maximize some objective function) that were found while including assessment error. More commonly, parameters that are optimal without assessment error are used in a comparison of control rules that includes assessment error. This approach can produce misleading results. Ideally, selection of a control rule and policy parameters is done within the framework of a stochastic simulation that considers key uncertainties. If this is not feasible, an alternative option is to "borrow" control rules from a similar fishery and set policy parameters based on biological reference points developed for a species with similar taxonomy and life-history traits. More research is needed to compare control rules when accounting for uncertainty in key population parameters, when stock–recruitment or other population dynamic parameters vary over time, and for fisheries with non-yield-based or competing objectives.

Contents

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1. Introduction

Rational management of fish stocks requires determination of harvest or yield levels that are consistent with management objectives. Historically, the "rules" for setting harvest levels have been vague or non-existent (NRC, 1994). In many cases, this resulted in forsaking long-term objectives for short-term gains. Consequently, examples of fish stock declines and collapses are widespread (Myers and Worm, 2005). To prevent future stock collapses, and allow rebuilding of stocks that are already depleted, more explicit guidelines are required on how harvest levels should be set. Such guidelines are referred to as harvest policies. When these guidelines specify the amount of catch, effort, or fishing mortality by a specific, and usually simple, function of the current estimate of the system state (e.g., the amount of spawning biomass) they are called control rules.

Fishery objectives partially determine the relative performance of different control rules and are represented quantitatively in simulations and analyses through the use of objective functions. Selection of objectives or objective functions can affect which control rule is preferred, and thus it is critical to ensure resource user preferences and broader societal goals for sustainability of the resource are incorporated into the chosen objectives. The use of an objective that conflicts with the interests of the fishery could cause mistrust from the fishing industry, or even fishery collapse. For example, in a recreational fishery, where high catch rates and the size of harvested fish are likely to be important, using a maximum yield objective function would be inappropriate. Although this is true, most harvest policy work emphasizes yield-based objectives, and hence by necessity, much of this review evaluates these.

Several methods are used to evaluate control rules for meeting given fishery objectives. A variety of analytical methods can be used to show that a given control rule performs better than all other candidates (i.e., is optimal) at achieving a given objective (e.g., Gatto and Rinaldi, 1976). While these methods can provide quite general results, they are feasible only for simple models of fishery systems that often are deterministic or ignore key uncertainties. Stochastic dynamic programming is an efficient method for selecting an optimal strategy at each time step, so that the result over the entire time-horizon best meets a specified objective (e.g., Walters and Parma, 1996). While the method can be analytical or numerical, most fishery applications are numerical. This method is useful when one is interested in considering more flexible policies than a simple control rule that remains constant over time. The computational cost of searching over a wide range of strategies has also generally limited this approach to relatively simple models. Much of the recent harvest policy literature considers models too complex for the above methods, and often the focus is on trade-offs among different measures of performance, rather than finding the policy that is optimal for a single objective. Consequently, much harvest policy work uses Monte Carlo simulations to evaluate the performance of a specified control rule (function) and policy parameters for the control rule (e.g., Eggers, 1993). Typically, multiplicative annual process error is included in the stock–recruit relationship, which may or may not include autocorrelation. Alternatively, or additionally, annual process error can be added to specific model parameters. Other random error terms are often included to model assessment or implementation error. When these simulations attempt to model uncertainty associated with the stock assessment process and implementation of the control rule, this is called a management strategy evaluation (MSE; Polacheck et al., 1999). Typically, a range of different policy parameters are considered. In some cases a wide enough range of policy parameters is considered that this essentially constitutes a grid search, and optimal results for a given control rule and objective can be identified. In rare cases, usually for very simple stochastic models, an automated numerical search is done for parameters that maximize an objective function. The results obtained by these "brute force" simulation approaches are limited to the specific policy parameters (and other assumptions) chosen for inclusion in simulations, and thus cannot prove that a particular control rule is optimal for a given objective over a broad range of conditions. However, we believe induction based on these studies, combined with consideration of results known from analytical studies, can be very useful.

In many fisheries, managers must decide on a level of yield each fishing season, ideally by using a harvest policy that is chosen because it meets fishery objectives (i.e., produces a large value for the objective function). Theoretically, a harvest policy could be to set yield each year so that the objective function is maximized given the information available at that time (Ricker, 1958; Larkin and Ricker, 1964; Tautz et al., 1969). Such a policy would generally mean that yield is determined in a complex way by current stock assessment results and other information (e.g., using stochastic dynamic programming; Frederick and Peterman, 1995). In practice, determination of such optimal policies can be a daunting or an infeasible computational task. Furthermore, such an approach can lack appeal to managers and stakeholders because the intuitive basis of the policy and why the current year's allowable catch has changed from the previous year may not be apparent. Perhaps as a consequence, nearly all harvest policies are based on relatively simple control rules that can be viewed as relating fishing mortality to stock abundance (usually biomass; Fig. 1). However, which rules are best at meeting certain fishery objectives is a source of controversy in the literature. Furthermore, the relative performance of control rules depends upon the specific characteristics of the fishery and underlying fish population dynamics that are incorporated into an evaluation. Consequently, selecting an appropriate control rule can be an arduous task.

The objectives of this review are to (1) compare and contrast the performance of various control rules for meeting common fishery objectives and (2) identify potential reasons for what seem to be contradictory results. First, we discuss a range of control rules and objectives that are used in harvest policy studies. Second, we consider the performance of different control rules when perfect knowledge is assumed about the fishery, after which we examine the effect of imperfect information on stock size, which is a feature of harvest policy analyses that has a particularly strong effect on control rule performance. Other features of harvest policy analyses also affect policy performance, such as the level of compensation in the stock–recruit relationship and whether certain stock–recruit parameters are autocorrelated through time, and these are addressed within the framework of the perfect and imperfect information sections. Third, we consider approaches

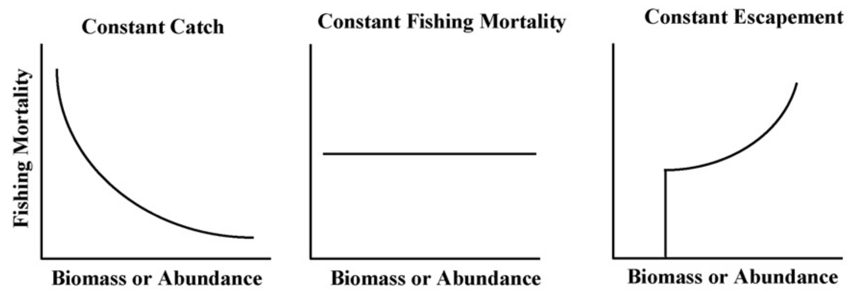

Fig. 1. Basic control rules and how fishing mortality generally changes with biomass or abundance for each type.

to choosing catch levels, fishing mortality rates, or thresholds necessary for implementation of control rules. Finally, we offer conclusions and suggestions for interpreting harvest policy analyses and identify future research needs.

2. Common control rules

We describe common control rules as background for our review of their relative performance. Most rules can be categorized into three main types (Fig. 1) or a few modifications of these (Fig. 2), and explicitly or implicitly specify a relationship between fishing mortality and stock abundance. We choose to specify control rules in terms of fishing mortality because how this per capita mortality rate varies with abundance summarizes the compensatory or depensatory effect of the rule. A constant catch control rule removes the same number or biomass of fish each year, and is depensatory in that it leads to high fishing mortality at low stock sizes (Fig. 1; Quinn and Deriso, 1999). A constant fishing mortality rate (also called a constant harvest rate) uses the same fishing mortality regardless of stock abundance (Fig. 1), and hence harvest is proportional to biomass (Quinn and Deriso, 1999). When fishing mortality is assumed to be directly proportional to fishing effort, constant fishing mortality rate rules are also referred to as constant effort. A constant or fixed escapement control rule takes all biomass over some specified target level. Control rules such as this are also referred to as "bang–bang" policies in the resource economics literature, because when modeled in continuous-time, harvest is intense above the threshold and zero otherwise (Fig. 1; Nostbakken, 2006). This type of control rule is often used when fishing anadromous fish, where a specified number of fish are allowed to pass a weir or other observation location and the remainder of the run is removed. In open-ocean or lake fishing, such a control rule is usually interpreted as allowing harvest of all fish over a threshold abundance or biomass, so that fishing mortality is zero up to that threshold and then increases thereafter (Fig. 1).

Each of these basic control rules has a number of variants, many of which have been suggested to retain what are viewed as positive features of a rule while addressing some of its weaknesses. Here we review some of these important variants (Fig. 2). The conditional constant catch (CCC) control rule, a variant of constant catch, removes the same number or biomass of fish each year unless removing that amount would exceed some predetermined maximum fishing mortality rate. If the constant catch amount would cause fishing mortality to exceed this rate, then the rule reverts to a constant fishing mortality rate at the predetermined maximum (Fig. 2B; Clark and Hare, 2004). This control rule attempts to avoid the high fishing mortality rates that occur at low stock sizes under a constant catch rule but retains the benefit of stable catches at high stock sizes. Murawski and Idoine (1989) and Hjerne and Hansson (2001) suggest similar control rules where the amount of harvest is reduced to a new low level (potentially zero) when biomass falls below a threshold (Fig. 2C).

Threshold control rules are suggested as modifications to constant fishing rate rules and specify a biomass below which no fishing is permitted (the threshold), but a constant fishing mortality rate is used otherwise (Fig. 2A; Quinn and Deriso, 1999). Variations

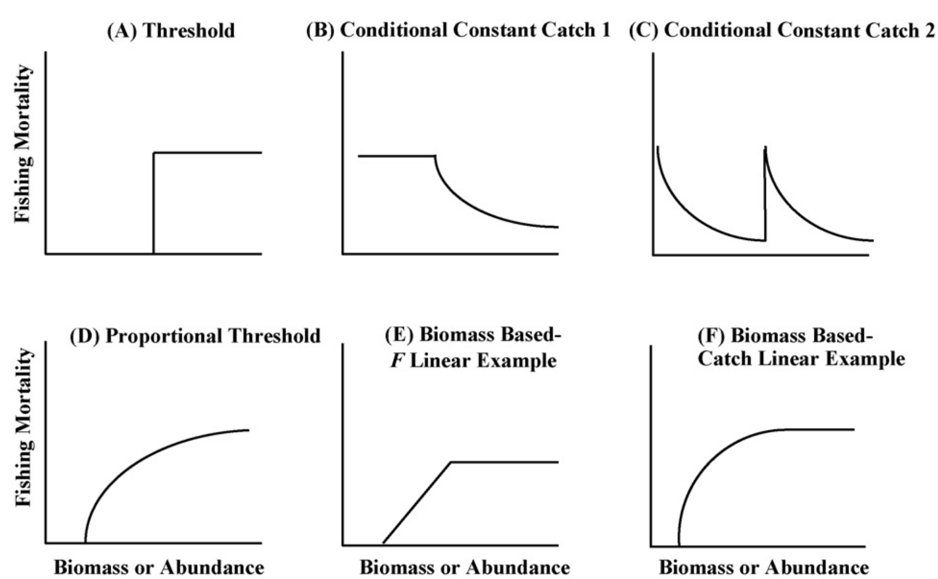

Fig. 2. Variants of basic control rules and how fishing mortality generally changes with biomass or abundance for each type.

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of this basic form have also been suggested, such as decreasing fishing mortality gradually below the threshold and increasing fishing mortality gradually above the threshold, to produce compensatory and potentially stabilizing fishing mortality (Fig. 2E; Quinn et al., 1990; Eggers, 1993; Sigler and Fujioka, 1993; Quinn and Deriso, 1999; Ishimura et al., 2005). Control rules that scale fishing mortality or catch downward when the population is below a threshold are known as biomass-based or adjustable rate rules, and fishing mortality or catch is usually adjusted in proportion to population size (Fig. 2E; Quinn and Deriso, 1999). Whether fishing mortality or catch is adjusted with changes in biomass affects the relationship between fishing mortality and biomass (Fig. 2E and F) and thus has potentially different performance characteristics. The "40-10" rule, which is used to manage U.S. west coast groundfish, is an example of the latter type of biomass-based rule. Catch is reduced linearly as spawning biomass declines below an upper threshold (40% of the unfished level) so that no harvest is allowed when spawning biomass is below a lower threshold (10% of the unfished level) (Hilborn et al., 2002; Punt, 2003; Punt et al., this issue). The result is that for a 40-10-like rule fishing mortality decreases nonlinearly (Fig. 2F). Engen et al. (1997) suggest a variation of a constant-escapement rule called "proportional threshold harvesting", which has been used to manage U.S. west coast pelagic species since the early 1980s (Pacific Fishery Management Council, 1998; Barange et al., in press). With this control rule, only a fraction of the surplus above the threshold is harvested. The resulting nonlinear relationship between fishing mortality rate and biomass can be viewed as a biomass-based control rule, and appears similar to a 40-10-like rule (Fig. 2D). Proportional threshold harvesting is a special case of a 40-10-like rule with the upper threshold set infinitely high (e.g., a "∞-10" rule). So, for both control rules catch increases linearly with biomass above a lower threshold, but for a 40-10-like rule the slope of the relationship changes above an upper threshold.

3. Common fishery objectives

Fishery objectives are represented in harvest policy analyses using objective functions, and these are used to compare the relative performance of control rules. A frequently used objective function is cumulative harvest over some fixed time horizon, or the sum of annual values of a utility function over a time horizon, where the utility function relates annual harvest to some economic, biological, or social construct (Quinn and Deriso, 1999). Maximizing cumulative harvest is considered a risk neutral approach, because performance is measured only by the total over the time horizon, with the frequency of low and high annual values playing no role (Reed, 1979; Quinn and Deriso, 1999). More risk-averse objective functions penalize for extreme harvests in an effort to avoid boom-or-bust fisheries (Walters and Pearse, 1996; Lande et al., 1997; Quinn and Deriso, 1999). One risk-averse objective function is to maximize the long-term logarithm of harvest, and this tends to avoid extreme harvests by placing an infinite penalty on zero harvests (Ruppert et al., 1985). This objective function, however, is criticized as being risk-averse only in terms of economic risk to the industry, and not biological risk to the resource (Lande et al., 1997). Another risk-averse objective function is to maximize a linear combination of average yield ($\bar{Y}$) and the negative of the standard deviation (S.D.) of yield over a given planning horizon (e.g., $\max[(1-\lambda)\bar{Y} - \lambda\,\text{S.D.}]$; Quinn et al., 1990; Collie and Spencer, 1993). This approach is relatively flexible in that the relative influence of average yield and the standard deviation of yield can be controlled using the weighting term, λ. An alternative, but less commonly used type of risk-averse objective accounts for how frequently or over what duration biomass or harvests have been at or below a threshold (Enberg, 2005; Irwin et al., this issue).

Other objective functions have been formulated to maintain biomass or harvest at predetermined target levels (Hightower and Grossman, 1987). This stability can be accomplished by minimizing the sum of squared deviations between biomass or harvest and the predetermined target levels. However, Hightower and Grossman (1987) criticize objective functions that only consider maintaining harvest near a target because two values of fishing mortality could result in the same equilibrium harvest. When rebuilding a stock from a depleted state, the optimal fishing mortality is the higher of the two equilibrium points, which also results in maintaining lower equilibrium abundance. Another criticism of only considering harvest is that, for an age-structured population, the same harvest is obtained for multiple age-structures. Consequently, when stock sizes decline, maintaining harvest near the target requires increasing fishing mortality, which can be destabilizing in terms of abundance and yield, creating a negative feedback (Beddington and May, 1977; Lowe and Thompson, 1993). To remedy these problems, Hightower and Grossman (1987) suggest using an objective function that simultaneously minimizes the deviations of both harvest and biomass from target levels. Similarly, the maximum harvest objective can also be combined with a constraint that requires the biomass at the end of the planning horizon to be near a target level (Hightower and Grossman, 1987). More generally, objective functions can be defined as even more complex functions of multiple performance measures (e.g., Katsukawa, 2004).

Bioeconomic objective functions that aim to maximize profits have also been developed (Clark, 1973). In a simple bioeconomic model, revenue R is assumed to be a linear function of harvest and is found as the product of price (amount paid per unit fish) P and harvest H:

$$R = PH;$$

(Clark, 1973; Reed, 1979; Quinn and Deriso, 1999). Costs C are incorporated into the model as the product of the cost per unit of fishing effort L and total effort E:

$$C = LE.$$

Net profit Q is the difference of the revenues and costs:

$$Q = R - C.$$

Costs can also be modeled as a function of stock size (Reed, 1979). Costs are most often modeled as a decreasing function of abundance, which requires the assumption that catch per effort (CPE) increases with abundance (Clark, 1973; Reed, 1979). Whether the decrease in cost as abundance increases is linear will depend upon whether catchability also varies with abundance (Reed, 1979). Bioeconomic objective functions can also incorporate discount rates, where the value of capital invested in the current time diminishes in the future due to inflation (Clark, 1973; Reed, 1979; Quinn and Deriso, 1999; Quinn and Collie, 2005). Objective functions incorporating discount rates are referred to as maximizing the expected present value (Reed, 1979). "High" discount rates have been blamed for the demise of some fish stocks, where the future value of capital approaches zero, so that economically, the optimal course of action is to fish the stock quickly to collapse (Clark, 1973). The use of negative discount rates is suggested by some conservation groups as a way to conserve stocks because capital actually increases in value in the future (Quinn and Deriso, 1999). Bioeconomic objective functions that maximize profits also tend to favor larger stock sizes than maximum yield objective functions (Clark, 1973; Deriso, 1987). Consequently, increasing effort beyond the point that attains maximum profits in order to achieve maximum yield is not only inefficient but can also incur other risks associated with smaller population sizes.

Table 1
Relative performance of control rules

Rank	No error in stock size estimates		Error in stock size estimates			
	Uncorrelated max recruitment	Correlated max recruitment	Uncorrelated max recruitment		Correlated max recruitment	
			Unadjusted policy parameters	Uncertainty adjusted policy parameters	Unadjusted policy parameters	Uncertainty adjusted policy parameters
Objective function: maximize yield or profits						
Better	Constant escapement	Constant-*F*	Proportional threshold	Constant-*F*	Constant-*F*	–
	Threshold/biomass based	Constant escapement	Constant Escapement	Threshold/biomass based	Constant escapement	–
	Constant-*F*	–	Constant-*F*	Constant escapement	–	–
Worse	Constant catch	–	–	–	–	–
Objective function: minimize risk of over-exploitation or maintain biomass above a threshold						
Better	Constant Escapement	–	Constant escapement	Constant-*F*	Constant-*F*	–
	Threshold/biomass based	–	Constant-*F*	Threshold/biomass based	Constant escapement	–
	CCC	–	–	Constant escapement	–	–
	Constant-*F*	–	–	–	–	–
Worse	Constant catch	–	–	–	–	–
Objective function: minimize stock rebuilding time						
Better	Threshold/biomass based	–	–	–	–	–
Worse	Constant-*F*	–	–	–	–	–
Objective function: minimize variability in yield or profits						
Better	Constant catch	–	Proportional threshold	–	Constant-*F*	–
	Constant-*F*	–	Constant escapement	–	Constant escapement	–
	Threshold/biomass based	–	Constant-*F*	–	–	–
Worse	Constant escapement	–	–	–	–	–

The rank order performance of control rules for meeting each of several different fishery objectives. Results given in columns of the table correspond to cases assuming no error in estimates of stock size, with the inclusion of error in estimates of stock size, with and without policy parameters adjusted for uncertainty, and with and without autocorrelation in the maximum level of recruitment (see text). When errors in stock size estimates were incorporated, studies that compared performance for control rules using the policy parameters that were optimal without these errors are "unadjusted"; studies that sought policy parameters that were optimal over the uncertainty are "uncertainty adjusted". When uncertainty in stock assessments was incorporated, rank order reflects finding for the highest levels of assessment error that were evaluated. When for a given table column there are no studies that evaluated relative performance of a control rule, these policies are missing (–).

4. Relative performance with "perfect" information

4.1. Comparing control rules

Analyses of harvest policies often assume that decisions are made with "perfect" information (i.e., no uncertainty or error), in terms of knowing the underlying dynamic system model and its parameters, in knowing the current state of the system (e.g., biomass), and in being able to implement regulations to achieve a desired result. Assuming perfect information allows for greater ease of computation, and likely reflects the common practice of setting harvest quotas based on a point estimate of abundance (Frederick and Peterman, 1995). Although many would agree that this is an unrealistic assumption for most stocks (e.g., Engen et al., 1997), the results of studies based on perfect information are still used as a guide, because they are viewed as likely to reflect qualitative differences and outcomes that can be expected from the application of various control rules under situations of "imperfect" information.

Assuming perfect information, constant-escapement rules generally perform best for maximizing cumulative yield, mean annual yield, or profits, usually followed in performance by threshold or biomass-based rules, constant fishing mortality rate rules, and lastly constant catch rules, although this general conclusion may also depend on assuming that maximum recruitment levels (i.e., the asymptote of a Beverton–Holt stock–recruit function) are temporally independent (Tables 1 and 2). For semelparous stocks (e.g., pacific salmon *Oncorhynchus tshawytscha*), Ricker (1958) shows that constant-escapement control rules produce 24–57% higher long-term average harvest than constant fishing mortality rate rules, depending on the shape of the stock–recruitment curve, when both the escapement level and fishing mortality rate are set to attain the maximum average yield. This general result is also supported by additional research on iteroparous species and for a broad range of conditions (e.g., various stock–recruit relationships) (Table 2). With surplus production models, a type III functional response, and autocorrelated consumption rate, threshold rules can produce greater than 100% higher average yield, higher sum of discounted yields, and higher sum of discounted rents than constant fishing rate control rules, depending on the level of autocorrelation in consumption rates (Collie and Spencer, 1993; Spencer, 1997). Constant fishing mortality rate control rules, however, can outperform constant catch rules in terms of yield by 29% or more (Jacobson and Taylor, 1985). Furthermore, even with catch set at maximum sustainable yield (MSY) or the level that maximizes net revenue, several other studies show that constant fishing mortality rate and biomass-based control rules provide higher long-term yield and profits (Table 2). Similarly, constant harvest rate rules can produce the same or modestly higher average yield than the various CCC control rules (Hjerne and Hansson, 2001; Clark and Hare, 2004).

In contrast to some of these studies, Walters and Parma (1996) show, using stochastic optimal control methods, that constant-escapement control rules are inferior to constant fishing mortality rate control rules in terms of maximizing yield when the asymptote parameter (maximum level of recruitment) of a Beverton–Holt stock–recruit model is autocorrelated. This discrepancy likely occurs because optimal constant-escapement control rules are highly sensitive to the maximum level of recruitment (Lande et al., 1997). When maximum recruitment is autocorrelated, controls on spawning biomass exert imperfect control on expected recruitment. Walters and Parma (1996) also report that with autocorrelated maximum recruitment, constant fishing mortality rate control rules attain at least 85% of the theoretical maximum long-term yield (not constrained by a constant control rule) for most populations. This result also holds true when other stock recruitment parameters (i.e., slope near the origin) are simultaneously autocorrelated with the asymptote parameter, but does not hold

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Table 2
Characteristics of various studies that have evaluated harvest policies

Studies	Maximum recruitment level		Stock size estimates		Control rules						
	Uncorrelated	Correlated	No error	Error	CC	CF	CE	Threshold	Biomass	CCC	40-10
Objective function: maximize yield or profits											
Ricker (1958)	X		X			X	X				
Larkin and Ricker (1964)	X		X			X	X				
Tautz et al. (1969)	X		X			X	X				
Gatto and Rinaldi (1976)	X		X			X	X				
Reed (1979)	X		X				X				
Jacobson and Taylor (1985)	X		X		X	X					
Koonce and Shuter (1987)	X		X		X	X			X		
Hall et al. (1988)	X		X			X	X				
Getz and Haight (1989)	X		X			X	X				
Butterworth and Bergh (1993)	X			X	X	X	X				
Collie and Spencer (1993)	X		X			X	X	X			
Eggers (1993)	X		X	X		X	X				
Steinshamn (1993)	X		X		X	X					
Lande et al. (1995)	X		X		X	X	X				
Walters and Parma (1996)		X	X	X		X	X				
Engen et al. (1997)	X			X			X		X		
Lande et al. (1997)	X		X	X		X	X		X		
Spencer (1997)	X		X			X		X			
DiNardo and Wetherall (1999)	X		X		X	X					
Polacheck et al. (1999)	X			X	X	X					
Hjerne and Hansson (2001)	X		X			X				X	
Sladek Nowlis and Bollermann (2002)	X			X		X	X	X			
Vasconcellos (2003)		X		X		X	X				
Clark and Hare (2004)	X		X			X				X	
Katsukawa (2004)	X		X	X		X		X	X		
Lillegard et al. (2005)	X			X		X	X	X	X		
Objective function: minimize risk of overexploitation or maintain biomass above a threshold											
Beddington and May (1977)	X		X		X	X					
Jacobson and Taylor (1985)	X		X		X	X					
Koonce and Shuter (1987)	X		X		X	X			X		
Getz and Haight (1989)	X		X			X	X				
Quiggin (1992)	X		X		X	X					
Butterworth and Bergh (1993)	X			X	X	X	X				
Eggers (1993)	X		X	X		X	X				
Sigler and Fujioka (1993)	X		X			X		X	X		
Steinshamn (1993)	X		X		X	X					
Zheng et al. (1993a)	X		X			X		X			
Lande et al. (1995)	X		X		X	X	X				
Lande et al. (1997)	X		X	X		X	X		X		
DiNardo and Wetherall (1999)	X		X		X	X					
Polacheck et al. (1999)	X			X	X	X					
Sladek Nowlis and Bollermann (2002)	X			X		X	X	X			
Vasconcellos (2003)		X		X		X	X				
Clark and Hare (2004)	X		X			X				X	
Katsukawa (2004)	X		X	X		X		X	X		
Objective function: minimize stock rebuilding time											
Hightower and Grossman (1987)	X		X		X			X			
Quinn et al. (1990)	X		X			X		X			
Polacheck et al. (1999)	X			X	X	X					
Objective function: minimize variability in yield or profits											
Ricker (1958)	X		X			X	X				
Larkin and Ricker (1964)	X		X			X	X				
Tautz et al. (1969)	X		X			X	X				
Gatto and Rinaldi (1976)	X		X			X	X				
Reed (1979)	X		X				X				
Jacobson and Taylor (1985)	X		X		X	X					
Koonce and Shuter (1987)	X		X		X	X			X		
Getz and Haight (1989)	X		X			X	X				
Butterworth and Bergh (1993)	X			X	X	X	X				
Collie and Spencer (1993)	X		X			X	X	X			
Eggers (1993)	X		X	X		X	X				
Lande et al. (1995)	X		X		X	X	X				
Walters and Parma (1996)		X	X	X		X	X				
Engen et al. (1997)	X			X			X		X		
Lande et al. (1997)	X		X	X		X	X		X		
DiNardo and Wetherall (1999)	X		X		X	X					

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Table 2 (*Continued*)

Studies	Maximum recruitment level		Stock size estimates		Control rules						
	Uncorrelated	Correlated	No error	Error	CC	CF	CE	Threshold	Biomass	CCC	40-10
Hjerne and Hansson (2001)	X		X			X				X	
Sladek Nowlis and Bollermann (2002)	X			X		X	X	X			
Vasconcellos (2003)		X		X		X	X				
Clark and Hare (2004)	X		X			X				X	
Enberg (2005)		X	X			X		X	X		
Ishimura et al. (2005)	X		X				X				X
Lillegard et al. (2005)	X			X		X	X	X	X		

Papers that compared harvest policies for meeting common fishery objectives assuming no error in estimates of stock size, with the inclusion of error in estimates of stock size, and with or without autocorrelation in the maximum level of recruitment (i.e., asymptote of a Beverton–Holt stock–recruit function). Specific control rules and characteristics included in each paper are indicated with a X.

true when other stock–recruitment parameters are autocorrelated by themselves. Few other studies evaluate the effect of autocorrelated recruitment on the relative performance of harvest policies (Table 2), and none systematically evaluate the influence of additional alternatives for the form of such autocorrelation.

Escapement and threshold control rules were developed to prevent overexploitation and maintain spawning biomass, and so such rules often maintain higher biomass, lower variation in biomass, and result in less chance of overexploitation than other control rules (Table 1; Getz and Haight, 1989). Escapement and threshold control rules maintain more consistent levels of biomass than other control rules, because other rules allow some harvest regardless of the level of stock biomass, which can be destabilizing in terms of abundance and yield (Beddington and May, 1977; Lowe and Thompson, 1993). The destabilizing nature of continued fishing as abundance declines is also made worse with depensation at low abundance (Collie and Spencer, 1993; Eggers, 1993; Walters and Parma, 1996), and this is one reason why some authors argue against control rules like constant fishing mortality rates (Lande et al., 1997). Several studies show that constant catch control rules consistently result in the maintenance of less biomass and more instances of stock collapse than other rules that provide the same or higher average harvest, likely because a constant catch control rule leads to high levels of fishing mortality at low abundance (Fig. 1; Table 2). Potter et al. (2003) conclude that if maximizing revenues or yield are not high priorities, as in a recreational fishery, a constant catch control rule may be useful to meet other fishery objectives (e.g., high recreational catch rates), but the catch level should be set low to prevent stock collapse. Alternatively, the CCC control rule of Clark and Hare (2004) can maintain higher average spawning stock biomass than a constant harvest rate control rule, but this depends on the constant catch level and ceiling harvest rate. Thus, the CCC control rule may be effective at preventing the high fishing mortality rates at low stock sizes that occur with a strict constant catch control rule.

As a consequence of fishery closures, threshold and biomass-based control rules are also usually the optimal rule for quick rebuilding of depleted stocks (Table 1; Quinn et al., 1990). Median rebuilding times to equilibrium biomass under a threshold control rule are shorter than a constant fishing mortality rate control rule (Quinn et al., 1990). Hightower and Grossman (1987) also show that the optimal rebuilding strategy is to cease fishing until the threshold biomass level is reached, and use constant fishing mortality above the threshold.

Relatively high yields and stable biomass almost always appear to come at the cost of higher variability in yield (Ricker, 1958; Gatto and Rinaldi, 1976; Reed, 1979; Lande et al., 1995, 1997). Constant-escapement control rules usually result in the highest variability in yield, followed by threshold and biomass-based control rules, constant fishing mortality rates, and then constant catch (Tables 1 and 2, but see Enberg, 2004). The high variability of yield in constant escapement and threshold control rules is caused by fishery closures in years when biomass is not above the predetermined level (Lande et al., 1997; Lillegard et al., 2005). Constant fishing mortality rate control rules do not require fishery closures, and so usually have less variability in yield than constant escapement and threshold control rules, but also lead to greater variability in population abundance. Constant fishing mortality rate control rules also perform best at maximizing logarithm of yield, an objective function that places an infinite penalty on zero harvest (Walters and Parma, 1996; Walters and Pearse, 1996; Lande et al., 1997). Intuitively, a constant catch control rule will have zero variability in catch, except in cases when abundance drops below the predetermined level of catch and requires closing the fishery, or management cannot react quickly enough to close the fishery after the catch limit has been attained (Koonce and Shuter, 1987; DiNardo and Wetherall, 1999). However, the stability in yield of the constant catch control rule comes at the cost of foregoing high yields at times when abundance is high, and the highest variability in population abundance and hence risk of fishery collapse (Beddington and May, 1977; Jacobson and Taylor, 1985; Quiggin, 1992; Potter et al., 2003). If consistent yields and a stable market have a "much higher priority" than maximizing revenue, yield, or minimizing risk of fishery collapse, then a constant catch control rule will be a competitive option (Quiggin, 1992; Steinshamn, 1993; Potter et al., 2003).

The differences among control rules in catch/yield variability can be substantial. In a simulation based on the northwestern Hawaiian Islands lobster fishery, mean yearly percentage change in catch was less for a constant catch control rule (yearly variation in catch for the constant catch rule was caused by fishery closures) than a constant fishing mortality rate control rule (about 43 and 156%, respectively) across a range of catch and fishing mortality rate levels (DiNardo and Wetherall, 1999). The various CCC control rules maintain some of the benefits of a constant catch control rule; they can produce less yearly variability in catch than a constant harvest rate strategy, with the relative difference in variability depending on the values used for the CCC control rule parameters (i.e., constant catch level and maximum harvest rate) (Hjerne and Hansson, 2001; Clark and Hare, 2004). Constant fishing mortality rate control rules can also produce standard deviations in annual yield half that of threshold control rules (Collie and Spencer, 1993), and Walters and Parma (1996) show that the advantage of constant fishing mortality over constant escapement in terms of yield constancy is enhanced when maximum recruitment is autocorrelated. The biomass-based "40-10" control rule also maintains much lower standard deviation of average annual catch than an optimal constant-escapement control rule (Ishimura et al., 2005).

4.2. *Effect of the stock–recruit relationship*

The relative performance of harvest policies, and the results of some studies discussed above, can depend on the form of stock–recruit relationship used, and particularly the extent of compensation in the relationship, particularly for threshold control rules. Consequently, caution should be used when interpreting analyses that compare various harvest policies because the results may depend on the amount of compensation assumed to exist in the stock–recruit relationship. When recruitment is highly compensatory (i.e., recruitment is weakly dependent on stock size), the potential benefits of a threshold control rule (i.e., maximum yield or revenue) fail to materialize because maintaining a given level of spawning stock no longer produces benefits in terms of recruitment, but yield is generally still more variable than other control rules due to fishery closures. Hightower and Lenarz (1989) assume recruitment decreases by 10% when the spawning stock is reduced by 50% from the pristine level, making recruitment highly compensatory, and show that a constant-escapement control rule produces only 2% greater mean harvest than a constant effort control rule, but CV of harvest is 49% higher. For South African anchovy *Engraulis capensis*, Butterworth and Bergh (1993) assume recruitment varies around a constant level independent of stock size and show that a constant fishing mortality rate control rule produces the same yield as a constant-escapement control rule, but with less yearly variability in yield and less risk of the stock falling below 20% of unfished biomass. Other studies that assume highly compensatory stock–recruit relationships, where recruitment is independent of stock size over a broad range, also report similar results for "40-10", constant catch, and constant fishing mortality rate control rules relative to threshold control rules (Steinshamn, 1998; Ishimura et al., 2005). If these analyses had included a weaker compensatory response in the stock–recruit relationship, the results likely would have been different, and the benefits of threshold control rules (maximum yield or revenue) may have been preserved.

5. Relative performance with "imperfect" information

In reality, management must be conducted with "imperfect" information (i.e., uncertainty), and intuitively, this uncertainty should dictate more conservative or robust harvest policies (Parma, 1993; Frederick and Peterman, 1995; Punt et al., 2002b; Quinn and Collie, 2005). Most work on the effect of such uncertainty on harvest policy performance is focused on the influence of errors in stock biomass estimates. Estimates of biomass that are too high will often result in catch levels that are too high, placing the stock at risk of overexploitation, or alternatively, increased catch may be sacrificed or the fishery may be closed unnecessarily when population estimates are too low (Parma, 1993; Engen et al., 1997; DiNardo and Wetherall, 1999; Milner-Gulland et al., 2001). Uncertainty in estimates of biomass can affect various performance measures used in comparing control rules used in harvest policy analyses, including yield, variability in yield, logarithm of yield, and probability of stock collapse. Generally, uncertainty in estimates of biomass causes decreased yield (or logarithm of yield), increased variability of yield, and increased probability of stock collapse for most control rules (Eggers, 1993; Walters and Parma, 1996; Walters and Pearse, 1996; Lande et al., 1997; Engen et al., 1997; Hilborn et al., 2002; Punt, 2003; Vasconcellos, 2003). Consequently, the sensitivity of different control rules to the presence of "imperfect" information can affect their relative performance (Table 1).

5.1. Policy parameters unadjusted for uncertainty

Most harvest policy analyses that compare control rules and account for uncertainty in stock size estimates do so by first obtaining harvest policy parameters that perform well without this uncertainty. They then compare the performance of control rules for these pre-specified policy parameters. This method essentially mimics a situation where managers are assumed to have chosen the policy parameters for a rule based on an analysis that did not account for stock assessment errors. Here we review studies of this type. In the next section we consider studies where policy parameters were "adjusted" for uncertainty.

With unadjusted policy parameters, the superior relative performance of a constant-escapement control rule for some performance variables is sensitive to errors in estimates of biomass (Table 1). Engen et al. (1997) show that proportional threshold harvesting results in larger expected cumulative yield than a constant-escapement control rule when uncertainty in biomass estimates are high, and nearly as large cumulative yield and less variation in yield when uncertainty in biomass estimates are at "lower" levels, a result also supported by more recent research (Milner-Gulland et al., 2001; Lillegard et al., 2005). Proportional threshold harvesting also reduces the frequency of fishery closures, and consequently yield variability (Engen et al., 1997; Lillegard et al., 2005). In contrast, uncertainty in stock size estimates appears to favor constant escapement over constant fishing mortality rate control rules, at least for the majority of studies where recruitment is varied in a temporally uncorrelated fashion about a stationary stock recruitment function; constant-escapement control rules (MSY level of escapement) generally produce higher average catch, average run size (i.e., number of spawners), average logarithm of catch, and lower CV of catch than constant fishing mortality rate control rules (i.e., MSY rate), and the disparity increases with increasing error (i.e., the constant rate rule is more sensitive) (Eggers, 1993; Sladek Nowlis and Bollermann, 2002). These results contrast with the results for "perfect information", where constant fishing mortality rate control rules are optimal for maximizing logarithm of catch and escapement rules typically have higher variability in catch due to fishery closures. The higher variation in catch for constant fishing mortality rate control rules in the presence of stock assessment errors may occur because higher than planned levels of fishing due to errors are not compensated for by subsequent reductions in fishing mortality. In the short-term, this could produce lower variation than a constant-escapement control rule, but in the long-term an increased variation in stock size can lead to increased variation in yield (Eggers, 1993).

A major caveat to the results presented in the previous paragraph is that a constant fishing mortality rate control rule can be favored over a constant-escapement control rule in terms of yield, regardless of the level of uncertainty in biomass estimates for at least one type of autocorrelated recruitment. Walters and Parma (1996) show that a constant fishing mortality rate control rule performs better in terms of yield when the asymptote parameter of a Beverton–Holt stock–recruit model is autocorrelated, even with uncertainty in biomass estimates. This result also holds true when other stock recruitment parameters (i.e., slope near the origin) are simultaneously autocorrelated with the asymptote parameter, but does not hold true when other stock–recruitment parameters are autocorrelated by themselves.

In contrast with the studies described above, Butterworth and Bergh (1993) and Polacheck et al. (1999) show that the relative performance of constant catch, constant fishing mortality rate, and constant-escapement control rules generally remain similar to situations of perfect information when uncertainty is added through the use of management strategy evaluations. These studies suggest that under some circumstances the relative performance of these control rules may be robust to the inclusion of uncertainty.

5.2. Uncertainty adjusted policy parameters

An alternative to using policy parameters that work best for a control rule without errors in stock size, is to select them so as to maximize the expected value of an objective function averaged over these (or other) errors (e.g., over simulations). The relative performance of various harvest policies can then be compared based on which policy produces a larger expected value of the objective function. Such studies mimic a situation where it is assumed that managers are taking into account uncertainty (e.g., in stock assessment) when they decide on policy parameters.

When this approach has been compared with the case of perfect information, more conservative fishing within a policy is again favored, and the relative performance of different types of control rules is changed. For example, Frederick and Peterman (1995) show that a constant fishing mortality rate control rule outperforms a constant-escapement control rule in terms of maximizing expected present value (measured in dollars) and preventing harvest from falling below 10% of the deterministic equilibrium level when uncertainty in the shape of the stock–recruit function (i.e., uncertainty in the parameters of a Shepherd function) and error in biomass estimates were accounted for. Frederick and Peterman (1995) also show that constant fishing mortality is favored in the case of depensatory recruitment, which might be expected to be more favorable to constant-escapement control rules (Ricker, 1958; Larkin and Ricker, 1964; Tautz et al., 1969; Collie and Spencer, 1993; Spencer, 1997). Katsukawa (2004) considers a wide range of policy parameters for a biomass-based control rule (Fig. 2), which includes constant fishing mortality rate and threshold control rules as limiting cases. The study shows that substantial errors in stock assessments favors control rules more like constant fishing mortality rate, whereas perfect information favors control rules that resemble threshold rules. That is, such control rules tend to produce as much yield while maintaining similar levels of biomass. Similarly, Sethi et al. (2005) uses stochastic optimal control methods to show that assessment error favors control rules that more closely resemble a biomass-based policy than a constant-escapement control rule, when the objective is to maximize discounted yield. Similar results have previously been reported by Clark and Kirkwood (1986). Vasconcellos (2003) also report higher and less variable yields for constant fishing mortality rate rules than for constant-escapement rules, although to some extent this could be partly due to probabilistically incorporating an autocorrelated asymptote to recruitment as in Walters and Parma (1996). Sethi et al. (2005) show that implementation error alone does not influence the form of the control rule, but it does appear to have an interactive effect with assessment error. These limited studies that consider uncertainty adjusted results contrast in an important way with the unadjusted results of the previous section; suggesting that accounting for uncertainty when estimating policy parameters is warranted.

6. Selecting catch, fishing mortality, and threshold levels

6.1. Available options—simulations or biological reference points

Once a general family of control rule is chosen, managers must then decide on policy parameters; the level of catch, fishing mortality, or threshold to apply. Ideally, this decision is made through a management strategy evaluation that uses stochastic simulation to incorporate uncertainty in stock assessments (e.g., parameter values and biomass estimates), population dynamics (e.g., stock–recruit function), and implementation (Annala, 1993; Francis, 1993; Frederick and Peterman, 1995, Polacheck et al., 1999). This approach evaluates the robustness of control rules and policy parameters to uncertainty, and prevents the need for selecting an arbitrary level or basing the harvest policy on some biological reference point (BRP) that may be too conservative or too aggressive depending on the stock. Furthermore, optimum levels of catch, fishing mortality, or thresholds often become more conservative as uncertainty in assessments increase, suggesting that estimates from deterministic simulations may be risk-prone (Lowe and Thompson, 1993; Gibson and Myers, 2004; Lillegard et al., 2005).

Although constructing a stochastic simulation is ideal, this is not always feasible due to data requirements and time and effort demands (Annala, 1993; Caddy and Mahon, 1995). Consequently, levels are often selected based on BRPs or historical experience (Caddy and Mahon, 1995). The use of BRPs requires defining the various reference points as targets or limits, but what qualifies as a target or limit can be confusing. Here we propose similar definitions for targets and limits as those of Caddy and Mahon (1995) and Caddy and McGarvey (1996). A target is a desirable state of the fishery (e.g., fishing mortality) or resource (e.g., biomass) at which management action should aim, so that on average the target is attained. A limit is a “dangerous” state of the fishery or resource that should be avoided or exceeded with only a “low” level of probability or frequency. In order to be effective, a limit must also be accompanied by some predefined management actions that are to be taken based on specific evidence that the limit is likely to have been exceeded, which would allow the fishery to rebound. Interpreting a limit as requiring that there is some predetermined “low” probability that the state of the fishery or resource will exceed the limit can be problematic. Estimating such probabilities would usually require a stochastic simulation model that considers key uncertainties, and often reference points are being used because such a model is not available. Managers can still make informed decisions, however, based on the historical performance of various BRPs, and whether those BRPs seem better suited as a target or limit, given characteristics of the fishery. Below we provide an overview of some of the reference point literature. For a more detailed description and evaluation of each BRP consult the references in Table 3.

6.2. Constant catch levels

MSY has historically been used as a target for constant catch control rules, but the pitfalls of MSY as a target are well known (Clark, 1973; Larkin, 1977; Sissenwine, 1978; Hilborn and Walters, 1992; Caddy and Mahon, 1995; Quinn and Deriso, 1999; Quinn and Collie, 2005). MSY now most often serves as a limit catch level or a starting point from which constant catch levels are scaled downward to more conservative targets (Hilborn and Walters, 1992; Annala, 1993; Overholtz, 1999; Mace, 2001). Maximum constant yield (MCY) is one example of a catch level conceptually similar to MSY, but considers random fluctuations in production, as opposed to assuming deterministic dynamics following a Schaefer surplus production model (Sissenwine, 1978; Murawski and Idoine, 1989). A critical feature of MCY is that as variation (and possibly autocorrelation) in production increases, given stock size, MCY decreases below MSY (Sissenwine, 1978; Getz et al., 1987). Sissenwine (1978), however, warns against using estimates of MCY as target levels because the fishing mortality rate associated with that level of catch can be high, and cause declines in spawning stock biomass and subsequent recruitment. In New Zealand during the 1990s, developed fisheries for which a population model was available to estimate MSY were managed with a constant catch level of 2/3 MSY (Annala, 1993). This level was selected based on stochastic simulation results that found that MCY can be as low as 60% of the deterministic MSY for some stocks (Annala, 1993). Constant catch levels in New

Table 3
Studies that evaluated various biological reference points (BRP)

BRP	References
Catch levels	
MSY	Clark (1973), Beddington and May (1977), Larkin (1977), Sissenwine (1978), Sissenwine and Shepherd (1987), Hilborn and Walters (1992), Caddy and Mahon (1995)
MAY	Sissenwine (1978), Getz et al. (1987), Murawski and Idoine (1989), Annala (1993)
MSY proxies	Beddington and Cooke (1983), Annala (1993)
Fishing mortality levels	
F_{msy}	Larkin (1977), Koonce and Shuter (1987), Hilborn and Walters (1992), Overholtz (1999), Mace (2001), Collie and Gislason (2001), Gibson and Myers (2004), Brodziak and Legault (2005)
$F = M$	Alverson and Pereyra (1969), Francis (1974), Deriso (1982)
F_{max} and $F_{0.1}$	Ricker (1975), Sissenwine and Shepherd (1987), Deriso (1982), Deriso (1987), Clark (1991), Jakobsen (1992), Goodyear (1993), Leaman (1993), Helser and Brodziak (1998), Collie and Gislason (2001), Campana et al. (2002), Rahikainen and Stephenson (2004)
$F_{x\%}$	Sissenwine and Shepherd (1987), Gabriel et al. (1989), Clark (1991), Goodyear (1993), Jakobsen (1993), Mace and Sissenwine (1993), Fujioka et al. (1997), Siddeek and Al-Hosni (1998), Clark (1993), Clark (1999), Collie and Gislason (2001), Clark (2002), Williams (2002), Booth (2004), Rahikainen and Stephenson (2004)
F_{ro}	Sissenwine and Shepherd (1987)
F_{rep}, F_{med}, F_{high}, F_{low}	Sissenwine and Shepherd (1987), Jakobsen (1993), Mace and Sissenwine (1993), Maguire and Mace (1993), Collie and Gislason (2001)
F_{st}	Quinn and Szarzi (1993), Hayes (2000)
Threshold levels	
Biomass thresholds	Quinn et al. (1990), Clark (1991), Mace and Sissenwine (1993), Overholtz et al. (1993), Sigler and Fujioka (1993), Thompson (1993), Zheng et al. (1993a), Zheng et al. (1993b), Myers et al. (1994), Fujioka et al. (1997), Quinn and Deriso (1999), Collie and Gislason (2001), Booth (2004)

Zealand have also been selected using other proxies for MSY, with the exact method of estimation depending on data availability and exploitation history of the fishery (Annala, 1993).

6.3. Constant fishing mortality rate F levels

Various BRP F values, for use in control rules that apply a constant F over all or some range of biomass levels, have been suggested as either targets or limits. F_{msy} was often used as a target, but has been criticized as being economically inefficient and difficult to estimate reliably, and so should likely be treated as a limit or benchmark from which more conservative fishing strategies are developed (Larkin, 1977; Koonce and Shuter, 1987; Sissenwine and Shepherd, 1987; Hilborn and Walters, 1992; Overholtz, 1999; Quinn and Deriso, 1999; Mace, 2001; Brodziak and Legault, 2005). Setting F equal to M was also suggested as a means to attain MSY, but this rarely holds true (Alverson and Pereyra, 1969; Francis, 1974; Deriso, 1982; Quinn and Deriso, 1999). Furthermore, the relationship between yield and fishing mortality rate is generally flat over a broad range of fishing mortality values, and so setting target fishing mortality rates below F_{msy} will often lose little in yield while maintaining a disproportionately higher amount of biomass (Deriso, 1987; Hilborn and Walters, 1992; Ralston et al., 2000; Dichmont et al., 2006b). Yield per recruit (YPR) analyses are used to formulate two common BRPs, F_{max} and $F_{0.1}$ (Deriso, 1987). Although sometimes used as targets, these reference points cause stock declines over a broad range of conditions and should likely be used as limits (Sissenwine and Shepherd, 1987; Clark, 1991; Jakobsen, 1992; Goodyear, 1993; Leaman, 1993; Campana et al., 2002; Rahikainen and Stephenson, 2004; Quinn and Collie, 2005). $F_{x\%}$ BRPs are based on spawning stock biomass or egg production per recruit (SSBR) analyses. These BRPs have the advantage that stocks with similar levels of compensation in the stock–recruit relationship can be cautiously managed with the same $F_{x\%}$ rate (Dorn, 2002). Combined with meta-analyses of stock–recruit data (e.g., Myers et al., 1999; Dorn, 2002), appropriate $F_{x\%}$ rates can be estimated where stock specific estimates of productivity are lacking. However, levels of $F_{x\%}$ (usually in the range of 20–40%) have historically been chosen based on yield objectives and were treated as targets (Clark, 1991; Ralston et al., 2000; Brodziak, 2002; Clark, 2002; Quinn and Collie, 2005). Because these levels of fishing were set without incorporating recruitment and biomass as part of the objective, it is not surprising that the selected $F_{x\%}$ levels have proved inconsistent with an objective of maintaining stock biomass above a specified threshold (Ralston et al., 2000). Several other BRPs have been developed using SSBR analyses and a plot of stock–recruit data. F_{ro} (for recruitment overfishing) is intended for use as a limit rate that explicitly avoids recruitment overfishing (Sissenwine and Shepherd, 1987). F_{rep} (for replacement), and similarly F_{med}, are suggested as targets to maintain current levels of biomass, but will only do so in the absence of density dependence in the stock–recruit relationship (Sissenwine and Shepherd, 1987; Mace and Sissenwine, 1993; Maguire and Mace, 1993; Quinn and Deriso, 1999). F_{low} and F_{high} are set relative to F_{rep} and would likely lead to rebuilding or stock declines, respectively (Jakobsen, 1993). F_{st} (for steady) is a BRP based on a Leslie matrix model that is conceptually similar to F_{rep} (Quinn and Szarzi, 1993; Hayes, 2000).

6.4. Threshold levels

Threshold levels, for use in threshold and biomass-based control rules, have been selected in a variety of ways. Perhaps the simplest method is to use a time series of abundance data. Sigler and Fujioka (1993) define sablefish stocks to be overfished whenever biomass falls below the historically lowest observed level. For over-exploited stocks, Overholtz et al. (1993) suggest using some percent level of biomass higher than current biomass. When a stock specific threshold cannot be determined, thresholds developed for other species with similar taxonomy and life-history parameters can also be applied (Mace and Sissenwine, 1993). Because these methods are somewhat arbitrary, the management action that should be taken when biomass falls below these levels is unclear.

Other less arbitrary biomass thresholds have also been developed. For populations exhibiting compensation, Quinn and Deriso (1999) show how a parameter can be added to a Graham–Schaefer surplus production model to estimate the point where latent productivity becomes zero or negative, providing a threshold level of biomass, which is often expressed as a percentage of unfished biomass. Zheng et al. (1993b) develop a similar methodology generalized to a depensatory surplus production model. When a stock–recruit relationship is taken into account, a more elaborate population model can be developed to estimate biomass at MSY for use as a target (or some other MSY proxy) and some level below MSY for use as a threshold (Quinn and Deriso, 1999). In the case of a depensatory stock–recruit relationship, the inflection point has been suggested as a threshold level of biomass, and assuming that growth and mortality are density-independent, the inflection point usually occurs below 20% of pristine biomass, suggesting that 20% is generally a threshold below which fishing should stop (Thompson, 1993). This conclusion is consistent with other studies that found that spawning biomass should be maintained between 20 and 50% of unfished spawning biomass as a way to ensure replacement and attain a large proportion of MSY (Quinn et al., 1990; Clark, 1991; Fujioka et al., 1997; Booth, 2004). Conversely, Myers et al. (1994) conclude that using 20% of unfished spawning biomass as a threshold may be risky for stocks with "severe" depensation, and recommend using the biomass level that produces 50% of the maximum recruitment as a robust threshold. Zheng et al. (1993b) suggest two methods of estimating thresholds based on life-history parameters called Fowler's method and May's method.

Many of the studies discussed above seek to determine a threshold independently from a target value of fishing mortality. In some cases the fishing mortality rate is set at levels that were determined as best for a constant fishing mortality rate control rule. An alternative is to simultaneously search for the threshold level and level of fishing mortality combination that maximize a given objective function in the framework of a stochastic simulation. Zheng et al. (1993a) and Quinn et al. (1990) use this approach with an objective function that considers both maximizing annual yield and minimizing yearly variations in yield. In accord with simulation results, we expect that the optimal fishing mortality rate at high biomasses would generally be higher for a biomass-based control rule than for a constant fishing rate control rule and thus there should be benefits to searching for the best combination. However, results are probably too limited to allow for rules of thumb on how much higher the fishing rate should be for a biomass-based control rule in the absence of an explicit analysis.

7. Summary and conclusions

Harvest policies are a necessary feature of transparent fisheries management because they ensure that the rules for how harvest will vary are evident to all stakeholders. However, the application of an inappropriate harvest policy will result in a failure to meet management objectives or potentially cause stock collapse. Rational management requires that objectives be explicitly stated and that a harvest policy is selected so as to best achieve those objectives. The results of this review provide some guidance on what control rules might be worth considering for given objectives, and what factors might influence their relative performance, and so should be included in analyses of harvest policies.

Most research to date focuses on evaluating harvest policies under the assumption of "perfect information" (i.e., no uncertainty or error; Table 2). These analyses often identify optimal control rules for meeting certain fishery objectives under given conditions, and highlight factors that might affect relative policy performance. Of particular importance seems to be the shape of the stock–recruit relationship (i.e., level of compensation), autocorrelation in recruitment, and whether depensatory mechanisms exist (Ricker, 1958; Larkin and Ricker, 1964; Tautz et al., 1969; Hightower and Lenarz, 1989; Collie and Spencer, 1993; Walters and Parma, 1996; Lande et al., 1997; Spencer, 1997; Steinshamn, 1998; Ishimura et al., 2005). Some research also suggests that variability in other population parameters, such as time-varying catchability, may also have an effect on relative policy performance (Punt, 1997; Punt et al., 2002b; Dichmont et al., 2006a; Dichmont et al., 2006c). We believe more needs to be learned about how temporal variation in parameters, such as those governing the stock–recruitment relationship, influences the performance of harvest policies.

Much less research focuses on comparing harvest policies while considering key uncertainties (e.g., in the recruitment function, error in biomass, error in catch statistics). One result of adding uncertainty is that policy parameters (e.g., a constant fishing mortality rate) are generally shifted in a more conservative direction from those based on treating point estimates of parameters governing population dynamics and fishery behavior as known. Thus, research that assumes perfect information should be interpreted cautiously, since uncertainty is a ubiquitous feature (Punt et al., 2002). Furthermore, the relative performance of control rules depends on whether the policy parameters have been adjusted for uncertainty. In general, we believe managers should adjust parameters for uncertainty as is advocated in the decision analysis literature (Peterman and Anderson, 1999). This conclusion suggests that much more research on the relative performance of control rules using uncertainty adjusted parameters is needed.

Greater uncertainty clearly reduces sustainable yields and other benefits of fishing. The policy studies reviewed here that incorporate uncertainty in stock status or underlying dynamics treat this as a constant fixture of the system. Additional studies are needed that take an adaptive management view, and consider the interaction between harvest policies and understanding of the fishery system (Walters, 1986).

Many resource economists conclude that constant-escapement control rules provide maximum profits, but they also generally do not consider the possibility of autocorrelated recruitment, uncertainty, and they often assume that profits are linearly related to harvest (Gatto and Rinaldi, 1976; Reed, 1979; Lande et al., 1995; Nostbakken, 2006). The linear relationship may not adequately consider the social and political repercussions of a frequently closed fishery. We believe this is why constant-escapement control rules are not applied more often. For example, in the South African anchovy fishery, a constant-escapement control rule was abandoned for a constant fishing mortality rate control rule within 2 years of being implemented because it became obvious that fishery closures would be frequent (Cochrane et al., 1998).

Most research focuses on single management objectives (e.g., maximizing yield) and the policies that are optimal for meeting single objectives. However, management often involves competing objectives, and selecting a harvest policy that is optimal for one objective involves a trade-off with some other objective (Quinn et al., 1990). For example, constant-escapement control rules that maximize long-term yield also often maximize variability in yield (Walters and Parma, 1996). McGlade (1989) proposes an intensive approach to deal with competing objectives called integrated fisheries management, which explicitly models ecological, socioeconomic, legal, and institutional aspects of a fishery into a single model. Management strategy evaluations can also address uncertainties that occur throughout the management process, including the ecological and socioeconomic aspects (Smith et al., 1999; Punt et al., 2002c; Dichmont et al., 2006a,b,c). These approaches might produce optimal policies that differ from traditional single objective approaches (McGlade, 1989). For example, consideration of how closing a fishery affects the short-term economics and social atmosphere of fishing communities would likely result in a different optimal policy than attempting to maximize long-term profits alone. Generally, little is known about optimal policies for meeting multiple competing objectives, and optimal policies in these situations might be different than has been found for single objective approaches (Fieberg, 2004).

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To deal with the trade-offs of competing objectives, some control rules attempt to attain "the best of both worlds". CCC control rules attempt to combine attractive aspects of constant catch and constant fishing mortality rate control rules, so as to attain stable catch with less risk than strict constant catch (Murawski and Idoine, 1989; Hjerne and Hansson, 2001; Clark and Hare, 2004). Biomass-based control rules are an alternative that avoids frequent fishery closures and responds to declining biomass by reducing fishing mortality, and so retains attractive features of constant fishing mortality (i.e., few fishery closures) and constant-escapement control rules (i.e., reduced harvest at low stock size). To date, little research has focused on these control rules, particularly in the presence of uncertainty. Furthermore, optimal methods for designing biomass-based control rules (i.e., exactly how *F* should decline with biomass) have not been developed and much work is needed on this and related topics.

Harvest policies are generally developed for single species fisheries, but increased awareness of problems caused with by-catch, increased centralization of fishery control, and increased knowledge of ecosystems may lead to attempts to apply harvest policies to entire food-webs or ecosystems (Walters et al., 2005; Quinn and Collie, 2005; Matsuda and Abrams, 2006). Walters et al. (2005) evaluates the ecosystem impacts of applying constant catch control rules to multiple species simultaneously, with the catch level set at MSY and estimated from single species assessments. They show that the ecosystem changes caused by such a strategy results in MSY being unattainable for several species and top predator populations most often declining. Similarly, Dichmont et al. (2006b) uses a management strategy evaluation for Australia's northern prawn *Penaeus* spp. fishery and shows that when species are caught simultaneously, multiple species cannot be sustainably harvested at individual F_{msy} rates. Matsuda and Abrams (2006) develop models to find the level of fishing effort that maximizes yield or profits from a food-web using simple linear rates of production and density dependence in growth for systems with as many as six species and five trophic levels. In many instances, maximizing yield or profits from the system involves eradicating top-predators in order to increase the production of lower trophic levels, particularly if the species in lower trophic levels are more valued. They conclude that further development of policies for entire food-webs may require preventative measures to ensure top predators are not eradicated for the sake of increased profits from lower trophic levels.

Fishing exerts selective pressures on fish stocks that can lead to the evolution of life-history traits that affect productivity (e.g., growth, age at maturity), and this may also affect relative policy performance (Heino, 1998; Conover and Munch, 2002; Swain et al., 2007). Little is known, however, about how sensitive policy performance is to evolutionary change, or whether such changes might also interact with other characteristics known to effect policy performance (e.g., uncertainty in estimates of biomass). This topic should remain an area of active research, and simulation studies that account for evolutionary change induced through harvest would provide valuable insight (e.g., Heino, 1998).

When an appropriate simulation study cannot be conducted to determine policy parameters (e.g., target constant fishing mortality rate) that best achieve stated objectives, BRPs likely provide the next best method for selecting fishing mortality rates and thresholds. The effectiveness of any BRP will depend on the objectives of the fishery and whether assumptions used in the development of a given BRP have been met. Generally, the shape of the stock–recruit relationship, and whether density-dependence or depensatory mechanisms are active will be of particular importance. Furthermore, if left with no better alternative, BRPs can be cautiously applied to species with similar taxonomy and life-history characteristics (Mace and Sissenwine, 1993).

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