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Original Article

Selecting relative abundance proxies for B_{MSY} and B_{MEY}

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The objectives for many commercial fisheries include maximizing either yield or profit. Clearly specified management targets are a key element of effective fisheries management. Biomass targets are often specified for major commercial fisheries that are managed using quantitative stock assessments where biomass is calculated and tracked over time. B_{MSY}, the biomass corresponding to Maximum Sustainable Yield, is often used as a target when maximizing yield is important, while B_{MEY} is the biomass target to maximize profit. There are difficulties in estimating both quantities accurately, and this paper explores default proxies for each target biomass, expressed as biomass levels relative to carrying capacity, which are more easily estimated. Integration across a range of uncertainties about stock dynamics and the costs of fishing suggests that a proxy for B_{MSY} in the range of 35–40% of carrying capacity minimizes the potential loss in yield compared with that which would arise if B_{MSY} was known exactly, while a proxy for B_{MEY} of 50–60% of carrying capacity minimizes the corresponding potential loss in profit. These estimates can be refined given stock-specific information regarding productivity (particularly the parameter which defines the resilience of recruitment to changes in spawning stock size) and costs and prices. It is more difficult to find a biomass level that achieves a high expected profit than a biomass level that achieves a high expected catch, because the former is sensitive to uncertainties related to costs and prices, as well as parameters which determine productivity.

Keywords: economics, management proxies, maximum economic yield, maximum sustainable yield.

Introduction

The theory of sustainable yield from fish stocks dates back to the 1930s (Russell, 1931; Hjort *et al*., 1933; Graham, 1935), and has gradually evolved into a system for managing fisheries to achieve long-term benefits from the resource while avoiding depleting stocks to levels where future productivity may be jeopardized (FAO, 1996). The twin objectives of sustaining high yields while avoiding overfishing are core to the modern concept of a well-managed fishery, notwithstanding that impacts of fishing beyond those on the target species are now also considered to be important and are embedded in the wider concept of ecosystem-based fisheries management (FAO, 2003; Pikitch *et al*., 2004). It is now widely recognized that specifying clear management targets for stocks is fundamental to achieving good fisheries management outcomes (as proposed in FAO, 1995).

Recognizing that any level of exploitation is expected to deplete a stock below its long-term average unfished biomass level, a major focus of practical fishery management in several jurisdictions including Australia, New Zealand and the US is to design regulations that achieve a target level of depletion (stock size relative to the unfished level) that achieves high sustainable yields and/or economic benefits from fishing. These somewhat different objectives (maximizing catch, and hence the associated level of economic activity, or maximizing economic returns) have been given expression in the concepts of maximum sustainable yield (MSY) and maximum economic yield (MEY). Depending on which objective is of primary concern, the target biomass reference point for the stock will be either B_{MSY} or B_{MEY} (the biomasses at which maximum sustainable yield and maximum economic yield are achieved). These quantities can either be treated as expected values (averages over time when fishing at a constant fishing rate) or point estimates given deterministic dynamics.

The theory of sustainable fisheries relies on the presumption that one or more biological processes (growth, natural mortality, recruitment) exhibit a density-dependent response to a reduction in population size, and hence that populations reduced below their nominal carrying capacities will tend to rebuild in the absence of fishing. This theory implies that there is a population size at which surplus production (the annual amount by which the population would increase in the absence of fishing) is maximized. The theory is supported by evidence that growth rates are density-dependent (Minte-Vera, 2004) and that recruitment exhibits a compensatory relationship with measures of reproductive potential (Myers and Barrowman, 1996; Myers *et al.*, 2002; although see Gilbert, 1997; Vert-pre *et al.*, 2013, for a counterview).

However, it was recognized as early as the 1930s (e.g. Russell, 1931) that fish stocks may have highly variable recruitment, and that catching an amount of fish equal to MSY in each and every year in perpetuity is unlikely to be an achievable objective, a view of MSY later taken more critically by Larkin (1977), Sissenwine (1978) and others. B_{MSY} remains a somewhat theoretical concept, the true value of which depends on assumptions such as the stationarity of functional relationships. As elaborated further below, the exact relationship between surplus production and biomass is unclear, but results of conventional models range from the theoretical B_{MSY} occurring at well below half of carrying capacity (typically inferred for productive and resilient species) to levels close to carrying capacity (typically assumed for unproductive and vulnerable species) (Fowler and Baker, 1991; Wade *et al.*, 2007). While not usually considered explicitly in management, relationships between surplus production and population size that are depensatory are also sometimes observed (Liermann and Hilborn, 1997, 2001). The use of limit reference points for biomass in harvest control rules, however, implicitly recognizes that there are stock sizes below which recruitment may be impaired. Modern usage of MSY-based targets and reference points accept the dynamic nature of fish stocks and often incorporate estimates of time variation in characteristics such as annual recruitment and growth.

Notwithstanding the many criticisms of B_{MSY} based on deterministic considerations, and ignoring interspecific and environmental effects, the concepts of MSY and B_{MSY} have played, and continue to play, a central role in fisheries management worldwide (Mace, 2001; Punt and Smith, 2001). While the need to maximize economic benefits from fisheries is widely acknowledged, to date only one country (Australia for its federally managed fisheries) has formally adopted B_{MEY} as the target biomass (Rayns, 2007; Kompas *et al.*, 2010). In contrast to B_{MSY}, which depends on biological considerations only, B_{MEY} also depends on assumptions regarding fishery dynamics and values for economic quantities such as fish prices and input costs (Dichmont *et al.*, 2010). Uncertainty about these quantities makes estimation of MEY and B_{MEY} even more challenging than estimating MSY and B_{MSY}. Nevertheless, in Australia at least, there remains a need to estimate MEY and B_{MEY} to implement the federal fisheries policy.

This paper explores the use of B_{MSY} and B_{MEY} as reference points employed in modern fisheries management, and some of the issues involved in estimating these quantities. We refer here to the biomass at which MSY or MEY is achieved, but the arguments apply equally well to the numbers of fish at which MSY or MEY is achieved, which forms the basis for management of cetacean populations subject to anthropogenic impacts. In particular, it examines the use of proxies for these quantities expressed as depletion levels, which should be easier to estimate and therefore manage towards, while still achieving the biological or economic goals of management.

B_{MSY}, B_{MEY} and their role in current fisheries management

Restrepo *et al.* (1998) interpret the National Standards in the US Magnuson–Stevens Act as prescribing that the fishing mortality rate F_{MSY} corresponding to B_{MSY} is a limit that should not be exceeded, while B_{MSY} is a lower bound for the target biomass level. The biomass below which a stock is declared to be overfished and in need of a rebuilding plan is 0.5 B_{MSY} or higher in the USA. Other countries such as New Zealand (Ministry of Fisheries, 2008) explicitly refer to B_{MSY} as a biomass level about which stocks should fluctuate. In Australia, the target biomass reference point is B_{MEY}, and the limit biomass reference point is B_{LIM} (directed fisheries are closed for stocks that are estimated to be below B_{LIM}). The Australian harvest policy (Rayns, 2007) allows for the use of proxies for both B_{MEY} ($1.2 \times B_{\mathrm{MSY}}$) and B_{LIM} ($0.5 \times B_{\mathrm{MSY}}$ or 20% of the average unfished biomass, B_0) (Smith *et al.*, 2009). Two limit reference points are used in New Zealand, a soft limit below which a formal rebuilding plan is required and a hard limit below which fisheries closures should be considered. The default value for the soft limit is $0.5 \times B_{\mathrm{MSY}}$ or 20% B_0 whichever is higher, while the default value for the hard limit is $0.25 \times B_{\mathrm{MSY}}$ or 10% B_0 whichever is higher (Ministry of Fisheries, 2008).

Article 31(a) of the World Summit on Sustainable Development also explicitly refers to a B_{MSY} target: "Maintain or restore stocks to levels that can produce the maximum sustainable yield with the aim of achieving these goals for depleted stocks on an urgent basis and where possible not later than 2015" (Anon, 2002). The goal to recover stocks to B_{MSY} is also reflected in directives in Europe (EC, 2011). The UN "Rio + 20" Conference on Sustainable Development resulted in an international commitment to rebuild fish stocks to "at least" B_{MSY} (UN, 2012). While it is not the purpose of this paper to evaluate whether fishery managers are able to maintain stocks at target levels, it is clear that B_{MSY} (and to a lesser extent B_{MEY}) continue to play an important role in management policy.

Estimating B_{MSY}

Although empirical methods for estimating B_{MSY} have been proposed (Boveng *et al.*, 1988; Goodman, 1988), their performance has been shown to be poor (Butterworth *et al.*, 2002). Therefore estimates of B_{MSY} (and F_{MSY}) are generally based on fitting models to data collected during fishery operations and surveys. There are three fundamental ways to estimate B_{MSY}:

(i) fitting biomass dynamics models (Butterworth and Andrew, 1984; Haddon, 2011) to catch and relative abundance index data;

(ii) calculating empirical measures of surplus production from catches and estimates of absolute abundance, and fitting a production function to these data (Hilborn, 2001; Worm *et al.*, 2009);

(iii) applying a stock assessment technique to estimate the relationship between spawning biomass and subsequent recruitment, and combining this relationship with models of yield- and spawning biomass-per-recruit as a function of fishing mortality (Sissenwine and Shepherd, 1987; Appendix 1). The estimation of the stock-recruitment relationship can be integrated into the stock assessment so the biomass time-series and the surplus production function are estimated simultaneously (e.g. Methot and Wetzel, 2013).

Approaches (i) and (ii) make no explicit assumptions regarding the specific biological processes which lead to surplus production, while approach (iii) bases estimation of the reference points on density-dependence in the stock-recruitment relationship, whether or not there is density dependence in other life-history parameters. The selection among these three approaches depends primarily on the data available. The first approach can be applied with only a time-series of catch and an index of relative abundance (such as fishery catch-rates or survey indices of abundance), while the second approach requires a time-series of catches and measures of population size in absolute terms (e.g. from surveys or from stock assessments). Approach (iii) requires the ability to estimate the form and parameters of the stock-recruitment relationship, which requires time-series of catch or survey age- or length-compositions in addition to time-series of catches and index data, although it is not uncommon for these methods to be applied pre-specifying the parameters which determines the *per capita* productivity of the population. Approach (iii) tends to be used commonly in the regions for which MSY-related targets and thresholds have been mandated, so are the focus of this paper.

Estimating B_{MEY}

For the purposes of this paper, B_{MEY} is taken to be an equilibrium concept (this differs from the dynamic interpretation of the MEY as it has been applied in, for example, the Australian northern prawn fishery (Dichmont *et al.*, 2010; Kompas *et al.*, 2010) and is computed as the maximum of the difference between steady-state revenue and costs, both of which are a function of effort (E) or fishing mortality. We use the terms MEY and B_{MEY} here as these terms are used conventionally in the policy arena. Given the definition of MEY and hence B_{MEY}, MEY and B_{MEY} could equally be respectively referred to as MSR and B_{MSR} (maximum sustainable rent and the biomass corresponding to maximum sustainable rent) (cf. Thompson, 1989). Consistent with its usage in Australia, we define economic return in terms of the value to the fishing industry at the point of landing, i.e. the revenue and costs we model are those of harvesters. The same arguments we make concerning MEY and B_{MEY} could be generalized beyond harvesters, for example to processors or even more generally to the community (local and/or national). However, doing so is beyond the scope of the current paper.

Figure 1a illustrates the calculation of E_{MEY} (75% of E_{MSY}) when the production function is quadratic, prices and cpue are constant over time, and the value of the parameter α is 0.5. α is the ratio of total costs to total revenues at MSY (Appendix 1). B_{MEY} for this case is 62.5% of carrying capacity. Figure 1b generalizes Figure 1a by showing values of B_{MEY}/B_0 for a range of choices for α. Ideally, the calculation of B_{MEY} would account for fish prices depending on demand and supply, as well as on fish size or sex, and for fixed as well as variable costs. However, the ability to quantify prices and costs to this extent (let alone predict prices and costs) is often difficult, and values for prices and particularly costs are uncertain.

B_{MSY} *and* B_{MEY} *in practice*

Notwithstanding the requirement in many jurisdictions that management be based on B_{MSY}, and the availability of methods for estimating B_{MSY}, very few stocks are managed using explicit estimates of B_{MSY}. Off the west coast of the USA (including Alaska), only three stocks of marine fishes (excluding salmon) are managed using an estimate of B_{MSY} based on approach (iii) above: Eastern Bering Sea walleye pollock (*Theragra chalcogramma*), Bering Sea and Aleutian Islands yellowfin sole (*Limanda aspera*), and Bering Sea and Aleutian Islands northern rock sole (*Lepidopsetta polyxystra*) (NPFMC, 2012). The Scientific and Statistical Committee (SSC) of the Pacific Fishery Management Council (which provides management recommendations for the fisheries in US federal waters off California, Oregon and Washington) states:

> "Stock assessment models that integrate the estimation of the spawner-recruit model also provide estimates of B_{MSY}. However, at this time, the SSC recommends that these estimates not be used as the target for rebuilding because they may not be robust. Rather, the rebuilding target should be taken to be the agreed proxy for B_{MSY} (e.g. $0.4 \times B_0$ for most groundfish stocks) in all cases" (PFMC, 2011).

In New Zealand, the biomass management targets, while guided by B_{MSY}, are often set higher than the estimate of B_{MSY}. For example, the estimates of B_{MSY} for two stocks of blue grenadier (*Macruronus novaezelandiae*; also referred to commonly as hoki) in New Zealand are, respectively, $0.24 \times$ and $0.25 \times B_0$. However, the

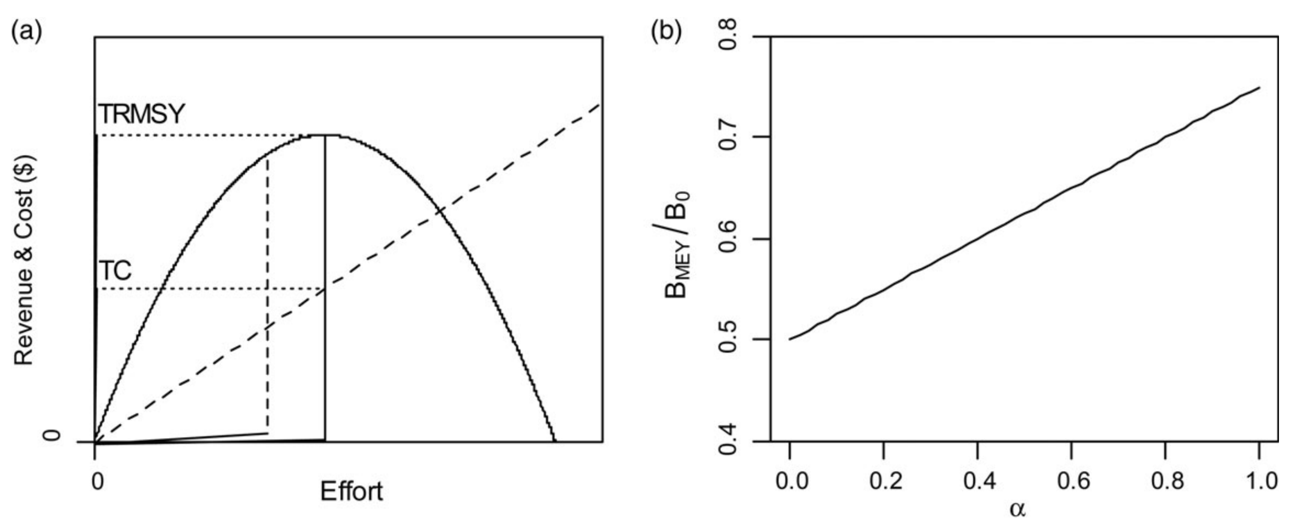

Figure 1. (**a**) Equilibrium revenue (under the assumption of constant price-per-unit-catch mass; solid line) and cost (dashed line) as a function of effort when surplus production is a quadratic function of biomass, and cost is a linear function of effort. The vertical dashed line in (a) indicates the effort at which the difference between cost and revenue is maximized (i.e. E_{MEY}). (**b**) Relationship between B_{MEY}/B_0 and α, where α is the ratio of total costs to total revenues at MSY [i.e. TC/TRMSY in (a)].

management target for these stocks is a range from $0.35–0.5 \times B_0$. Reasons given (Ministry of Fisheries, 2011) for not using the estimates of B_{MSY} as the target reference point for these fisheries include that its derivation involves the assumption of perfect information regarding the population and fishery dynamics, including the form and parameters of the stock-recruitment relationship, which is unrealistic. The Ministry of Fisheries (2011) also notes that a target of deterministic B_{MSY} would likely lead to an undesirably high probability of dropping below the limit reference point ($0.2 \times B_0$) for the blue grenadier fishery in New Zealand.

Federally managed fisheries in Australia are managed to achieve MEY (Rayns, 2007). However, B_{MEY} is estimated explicitly for only three Australian fisheries. The northern prawn fishery is managed using a dynamic bioeconomic model (Kompas *et al.*, 2010); the value of B_{MSY} for this fishery is not used explicitly for management purposes. The target biomass is $1.2 \times B_{MSY}$ for the tiger flathead (*Neoplatycephalus richardsoni*) fishery in the Southern and Eastern Scalefish and Shark Fishery (SESSF) (Smith and Smith, 2001), and B_{MSY} is estimated within the stock assessment. The Total Allowable Catches for the Great Australian Bight trawl fishery are set using average values for B_{MEY}, based on estimates derived from a multispecies bioeconomic model (Kompas *et al.*, 2011). B_{MEY} is set to 120% of the proxy for B_{MSY} for other Australian federally managed fisheries (Rayns, 2007). Although B_{MSY} is an output of the assessments for many Australian federally managed fisheries, the proxy for B_{MSY} of $0.4 \times B_0$ is used rather than the estimated value because of concerns regarding the robustness of those estimates (see below).

Management of stocks for which direct estimates of B_{MSY} are not available or not used are based on proxies (see Table 1 for examples of common proxies for estimating B_{MSY}). This paper explores reasons for not using estimates of B_{MSY} and B_{MEY} even when the assessment methods, e.g. those implemented in Stock Synthesis (Methot and Wetzel, 2013) and CASAL (Bull *et al.*, 2012), implicitly estimate a surplus production function and, given economic information, it is relatively straightforward to estimate B_{MEY} (at least if prices and cpue are assumed to be constant). The analyses presented are based primarily on the fisheries for blue grenadier and tiger flathead off southeastern Australia, but the issues considered are generic, and the qualitative results likely robust for other "groundfish" life histories.

Case study overview: blue grenadier and tiger flathead off southeastern Australia

Blue grenadier

Blue grenadier is found from New South Wales around southern Australia to Western Australia, including the coast of Tasmania. It is a moderately long-lived species with a maximum age of ~ 25 years. Age at maturity is ~ 4 years for males and ~ 5 years for females (length-at-50%-maturity for males and females is 57 cm and 64 cm, respectively) (Russell and Smith, 2006). Spawning occurs predominantly off western Tasmania in winter (Russell and Smith, 2006). Adults disperse following the spawning season and, while fish are found throughout the southeast region during the non-spawning season, their range is not well defined.

The fishery for blue grenadier off southeastern Australia is part of the SESSF. Blue grenadier is caught by demersal and midwater trawling. The total allowable catch since 2009/10 has been 4700 t, although previous landings have been as high as 9200 t, and this fishery is currently the largest by volume in the SESSF. There are two defined subfisheries (Punt *et al.*, 2001): the spawning (western Tasmania from June–August) and non-spawning fisheries (all other months and areas). The spawning fishery has taken the bulk of the catch since the 1996/97 season (currently 3:1 spawning:non-spawning).

The stock assessment for blue grenadier is the most data-rich in the SESSF. Apart from landings data by subfishery, information available to characterize stock size, productivity and quantities such as B_0 and B_{MSY} include a time-series of commercial catch-rate indices (standardized to remove the impacts of some of the factors unrelated to abundance), two estimates of absolute abundance from an egg production method, eight estimates of absolute abundance from acoustic surveys, estimates of discards in the trawl fishery from 1995, length-frequency data from 1981 (essentially the start of the fishery), and age composition data from 1984 (Tuck *et al.*, 2012). This stock assessment is implemented in Stock Synthesis. It estimates the unfished equilibrium biomass, B_0, the parameters of the growth curve by sex [growth is allowed to vary over time, owing to evidence for cohort-specific growth (Punt *et al.*, 2001; Whitten *et al.*, 2013)], natural mortality (assumed to be sex-specific, but independent of age and time), the parameters of functions which characterize fishery selectivity, and annual deviations about the stock-recruitment relationship. The stock-recruitment relationship is assumed to have the Beverton–Holt form with steepness (h, the expected fraction of unfished recruitment when spawning biomass is reduced to 20% of unfished spawning biomass) set to 0.75. Steepness is set to 0.75 based on Francis (2009) who showed that there was little information on steepness for blue grenadier in New Zealand and that results of a meta-analysis of steepness values in Myers *et al.* (1999, 2002) suggested a value lower than 0.9, which had been used in earlier assessments of blue grenadier in Australia and New Zealand.

Tiger flathead

Tiger flathead are endemic to Australia and are mainly caught on trawlable grounds in continental shelf and upper slope waters from northern New South Wales to Tasmania and through Bass Strait (Klaer, 2011). The length-at-50%-maturity is ~ 30 cm, corresponding to an age of ~ 3 years. The fishery for tiger flathead has been one of the mainstays of the SESSF for almost a century. While fluctuating widely over the duration of the fishery, catches by federally licensed fishers have averaged 2640 t over the past 15

Table 1. Examples of common proxies for B_{MSY}.

Proxy	Regions/Fisheries using proxy
40% of B_0	Australia; rockfish and groundfish off the US west coast; most New Zealand fish stocks
25% of B_0	Flatfish off the US west coast
$B_{35\%}$ multiplied by average recruitment "at B_{MSY}"	Crab stocks in the North Pacific
Range of biomasses selected by the assessment group	Crab stocks in the North Pacific; New Zealand rock lobster

$B_{35\%}$ = the mature male biomass-per-recruitment when fishing mortality is set equal to $F_{35\%}$, the fishing mortality rate that reduces mature male biomass-per-recruitment to 35% of its unfished value.

years, making the fishery for this stock the second largest by catch weight in the SESSF.

The tiger flathead fishery can be traced back to 1915, when tiger flathead formed the primary target species of steam trawlers that operated off New South Wales (Colefax, 1934). This trawl fleet operated until the early 1960s. A Danish seine fishery started in the 1930s and was the main method of catching tiger flathead during the 1950s and 1960s. The era of modern trawling commenced in the 1960s (Smith and Smith, 2001).

The assessment for tiger flathead in the SESSF is also implemented in Stock Synthesis, and is fairly data-rich. Catch data are available from the earliest years of the era of the steam trawlers (1915), and catch-rate data are available for several sectors of the fishery including the early trawlers (1919–57), the Danish seiners (1950–78) and the trawl fishery in recent (post-1986) years. Data on discards are available from an observer program since 1994, and length-frequency data are available from 1945. Age composition data are sparser, with the earliest age data being from 1998. The stock assessment estimates B_0, the steepness of the Beverton–Holt stock-recruitment relationship, h, some of the parameters of the growth curve by sex (growth is assumed to be time-invariant for tiger flathead), the parameters of functions that characterize fishery selectivity, and annual deviations about the stock-recruitment relationship.

What is needed to estimate B_{MSY} and B_{MEY}?

Analytical estimation of the surplus production function, and hence B_{MSY} based on an age- or size-structured population dynamics model, involves first postulating which biological parameters are density-dependent. Consistent with current practice, natural mortality and growth are assumed to be density-independent, while the stock-recruitment relationship is density-dependent for the purposes of the analyses of this section. Given the assumptions underlying the structure of the model, the surplus production function depends on the values assumed or estimated for natural mortality, growth, and selectivity as a function of age/length, together with the form and parameterization of the stock-recruitment

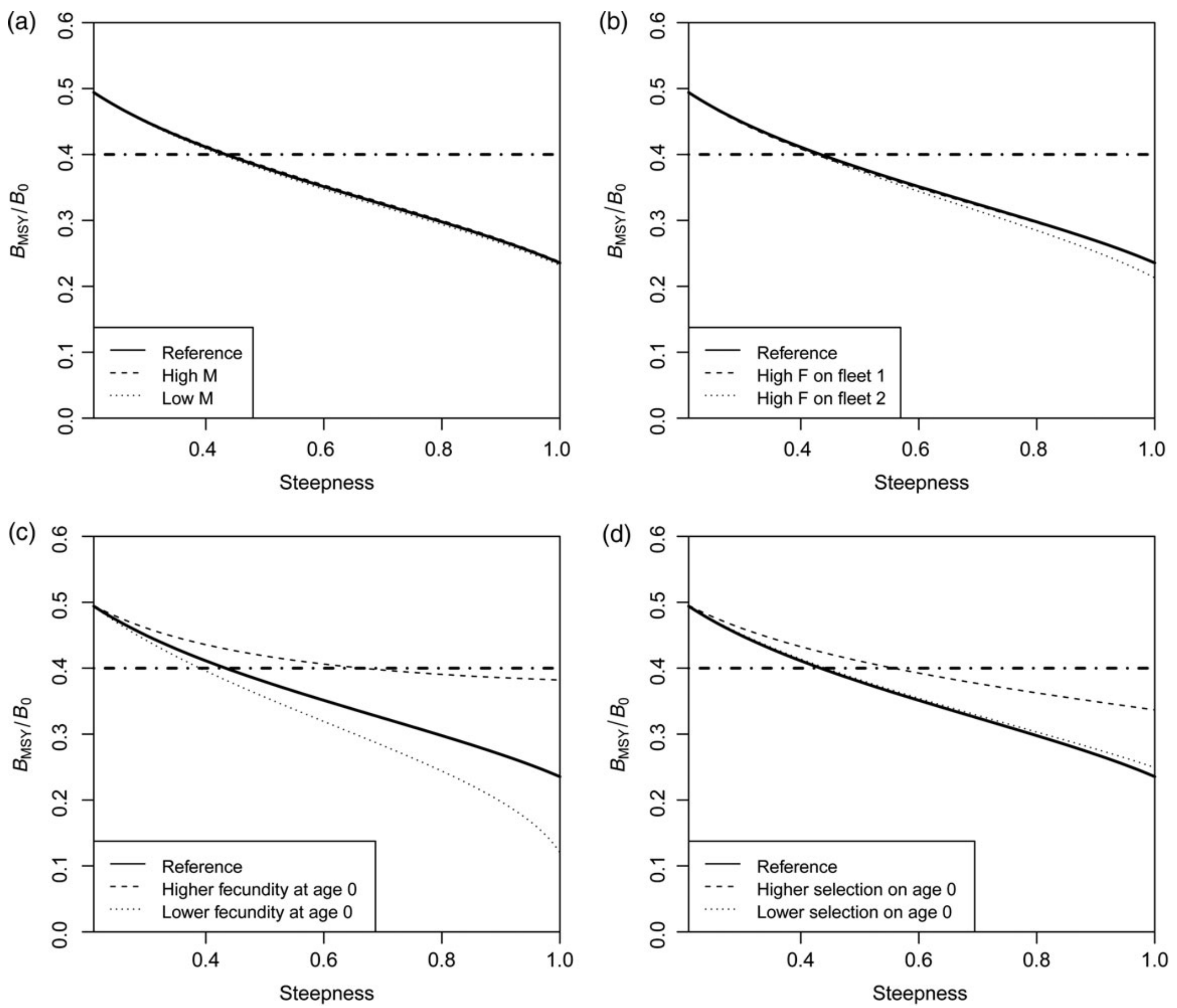

Figure 2. Relationship between B_{MSY}/B_0 and steepness for blue grenadier when the stock-recruitment relationship has the Beverton–Holt form. The horizontal line indicates the current proxy for B_{MSY} for blue grenadier. The results for the two choices for M are identical to those for the reference case, while the results for high F for fleet 1 are virtually identical to the reference case.

relationship (Appendix 1). Under the assumption that costs are proportional to fishing mortality and price is independent of the size of the catch and its age/size/sex-structure, B_{MEY} can be estimated as the biomass corresponding to the fishing mortality rate (or effort) at which the difference between cost and revenue is maximized (Figure 1a; Appendix 1).

It is well known that a key parameter determining the value of the ratio B_{MSY}/B_0 is the shape of the stock-recruitment relationship (e.g. Punt *et al.*, 2008). For the Beverton–Holt form of the stock-recruitment relationship, B_{MSY}/B_0 is a decreasing function of steepness, with a maximum (at steepness ~0.2) of ~0.5, declining monotonically to ~0.2 at a steepness of 1 for the reference parameters for blue grenadier (Figure 2, solid line). However, the value of this ratio will also be influenced by the rate of natural mortality, the relative fishing mortality by each of the spawning and non-spawning fleets, and the relationship between selectivity and fecundity by age. Figure 2 plots B_{MSY}/B_0 for blue grenadier against stock-recruitment steepness when the stock-recruitment relationship has the Beverton–Holt form (results for tiger flathead are qualitatively identical) for a reference set of parameters and a number of sensitivity tests. The results are robust to the specifications of the sensitivity tests so these are not outlined in full, but they include changing the nature of the selectivity pattern, the value for natural mortality, etc. The relationship between B_{MSY}/B_0 and steepness for blue grenadier is essentially independent of natural mortality and of which of the spawning or non-spawning fleets impose the greatest fishing mortality (Figure 2a and b). The relationship between B_{MSY}/B_0 depends on the relationship between fecundity and selectivity, i.e. that between spawning and fishable biomass (Figure 2c and d). Yield depends primarily on the size of the fishable biomass. Hence, for example, higher fecundity at age-0 means that a greater fraction of the total spawning biomass is protected from fishing for a given fishing mortality rate, and vice versa.

Given the relative lack of sensitivity to the choice of biological and fishery parameters, the following exploration of the ratios B_{MEY}/B_0

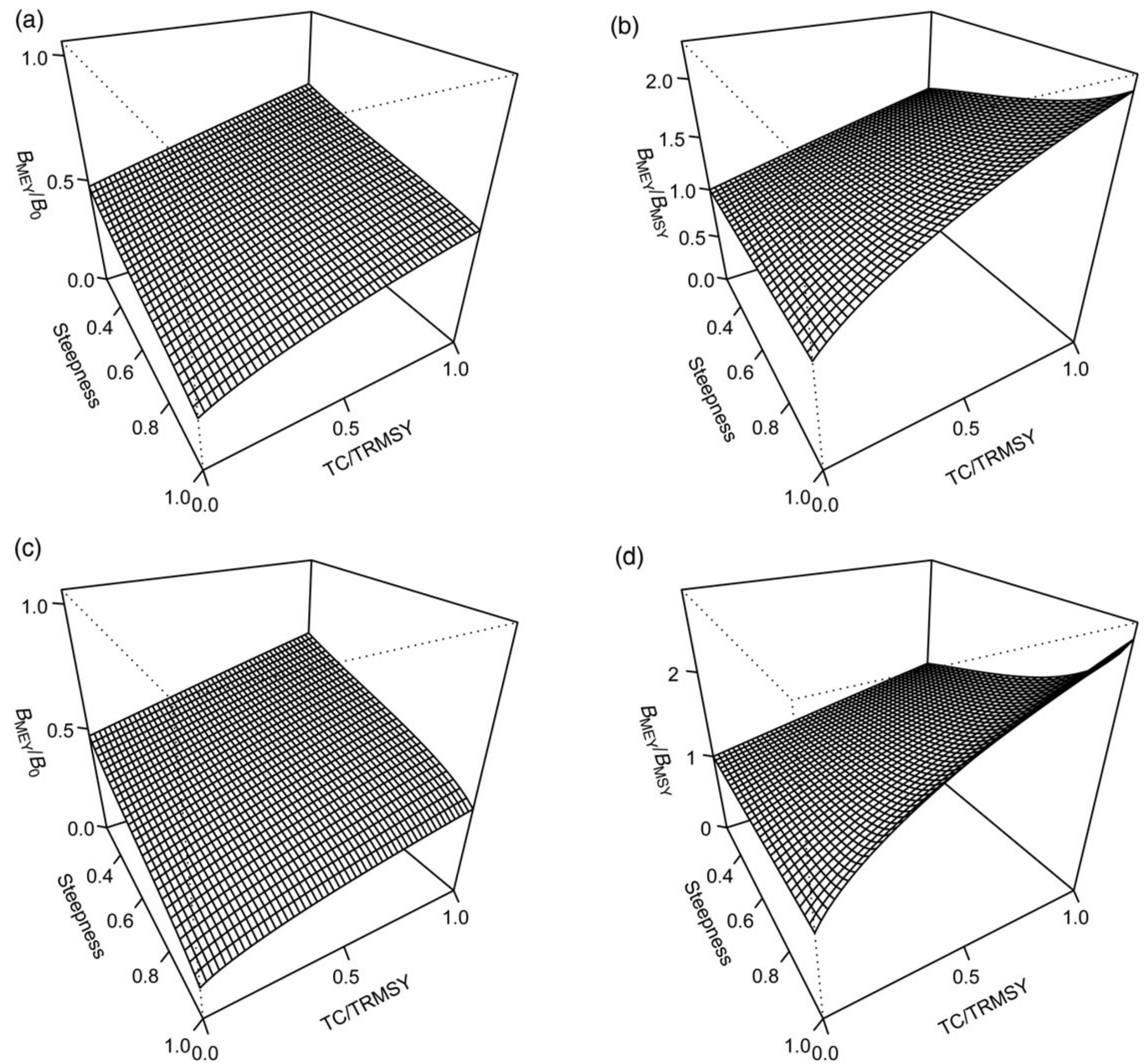

Figure 3. B_{MEY}/B_0 versus steepness and α = TC/TRMSY (left panels) and $B_{\text{MEY}}/B_{\text{MSY}}$ versus steepness and α (right panels) for blue grenadier (upper panels) and tiger flathead (lower panels). The stock-recruitment relationship has the Beverton–Holt form for these analyses.

and B_{MEY}/B_{MSY} only considers sensitivity to shape of the stock-recruitment relationship and the parameter that determines the fraction of the revenue at B_{MSY} "lost" to costs, α. Figure 3 shows these relationships for blue grenadier and tiger flathead for α in the range 0–1 (although α is not constrained to be less than 1). B_{MEY}/B_0 is higher for lower values of steepness and for higher values for the cost multiplier α for the case where the stock-recruitment relationship has the Beverton–Holt form. Although not shown in Figure 3, $B_{MEY}/B_0 = 1$ for high values for the cost multiplier because the profit is close to being negative for almost all values of fishing mortality. The ratio B_{MEY}/B_{MSY} ranges from 1 when $\alpha = 0$ to values in excess of 4 when steepness and the cost multiplier are high.

How well can B_{MSY}/B_0 and B_{MEY}/B_0 be estimated?

The ability to estimate B_{MSY}/B_0 has been explored using simulations and by applying stock assessment methods to actual datasets. Haltuch *et al.* (2008) used simulations to evaluate a large number of potential estimators for B_0, B_{MSY} and current depletion for three life-history types, and showed that estimation performance for B_0 and current depletion is much better than for B_{MSY} when a reliable catch history is available. This is perhaps unsurprising because stocks may pass through B_{MSY} fairly quickly, leading to little ability to detect where surplus production is maximized using stock assessment models. Haltuch *et al.* (2008) also suggest that estimating B_{MSY} from the fit of the stock-recruitment relationship performed best for two of the life histories they explored (rockfish- and flatfish-like), while multiplying average recruitment over the historical period by a spawning-biomass-per-recruit proxy for B_{MSY} such as $B_{40\%}$ performed best for a hake-like species. Haltuch *et al.* (2008) found that of the 26 methods for estimating B_{MSY} they evaluated, using the outputs from a stock assessment method that integrated the estimation of the stock-recruitment relationship into the assessment

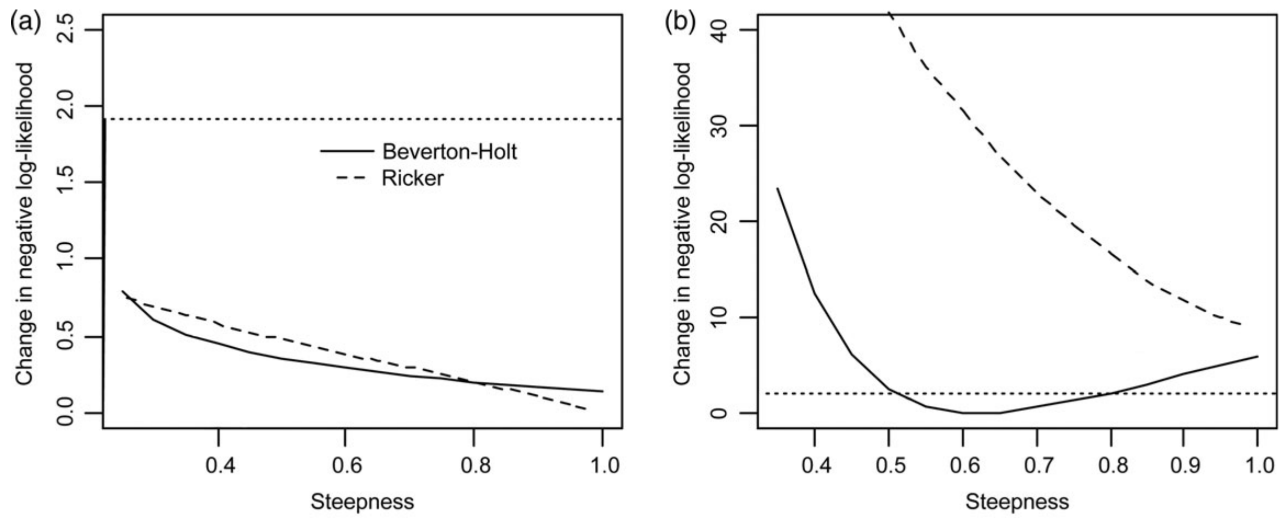

Figure 4. Difference in the negative log-likelihood from the lowest negative log-likelihood over stock-recruitment relationships and values for steepness as a function of the assumed value for steepness (the dashed line indicates the threshold for a 95% confidence interval) for the Beverton–Holt and Ricker stock-recruitment relationship. Results are shown for blue grenadier (**a**), and tiger flathead (**b**).

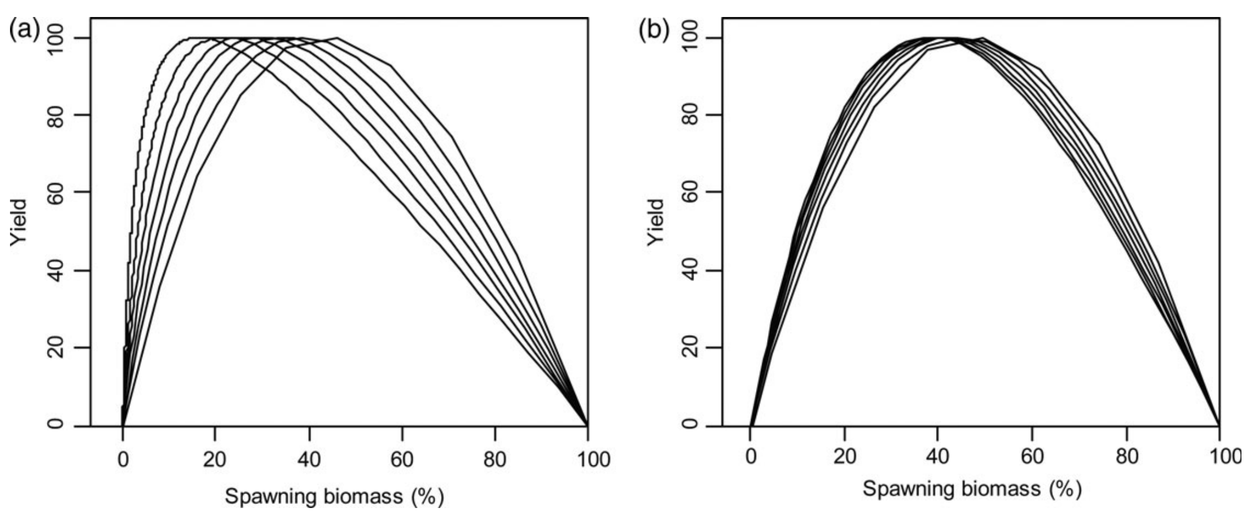

Figure 5. Relative yield versus spawning stock size for Beverton–Holt (left panel) and Ricker (right panel) stock-recruitment relationships. Results are shown for steepness values between 0.3 and 0.9 (steepness decreases from left to right in these panels; i.e. B_{MSY}/B_0 is lowest for the highest values for steepness).

performed "best" (although often not very well). The analyses in Haltuch *et al.* (2008) were predicated on knowing the true form of the stock-recruitment relationship (in their case, the Beverton–Holt form of the stock-recruitment relationship), knowledge of the functional forms governing selectivity-at-length and growth, as well as having a reliable catch history. Estimating B_{MSY}/B_0 is equivalent to estimating the steepness of the stock-recruitment relationship in this case and, consistent with a poor ability to estimate B_{MSY}/B_0, Haltuch *et al.* (2008), Lee *et al.* (2012) and Conn *et al.* (2010) also show that steepness is generally poorly estimated. Estimation of B_0 and depletion is likely poor for stocks for which recruitment is highly variable or even episodic unless catch and abundance data are available from at least the start of the fishery.

Proxy methods for estimating B_{MSY} were found to perform fairly poorly by Haltuch *et al.* (2008), even though B_0 was estimated relatively well. Horbowy and Luzenzzyk (2012) found that proxy estimates for F_{MSY} based on reductions in spawner biomass-per-recruit performed better than estimates of F_{MSY}, except surprisingly when the stock-recruitment relationship was mis-specified.

Figure 4 shows likelihood profiles for steepness for blue grenadier and tiger flathead for assessments based on the Beverton–Holt and Ricker stock-recruitment relationships. The likelihood profiles for blue grenadier indicate that the available data do not provide support for any value for steepness (Figure 4a), and hence that B_{MSY}/B_0 could occur at any point across the range 0.16–0.45 (as inferred, for example, from Figure 2). This result is perhaps not surprising because the stock of blue grenadier has not been depleted substantially (not lower than 80% of carrying capacity). In contrast, the data for tiger flathead do allow some values for steepness, and hence B_{MSY}/B_0, to be excluded (Figure 4b). Nevertheless, the 95% confidence interval for B_{MSY}/B_0 consistent with the data remains broad even for tiger flathead (~0.2–0.35). The profiles for the Beverton–Holt and Ricker stock-recruitment relationships differ for tiger flathead. However, a Ricker steepness of 1 shows similar

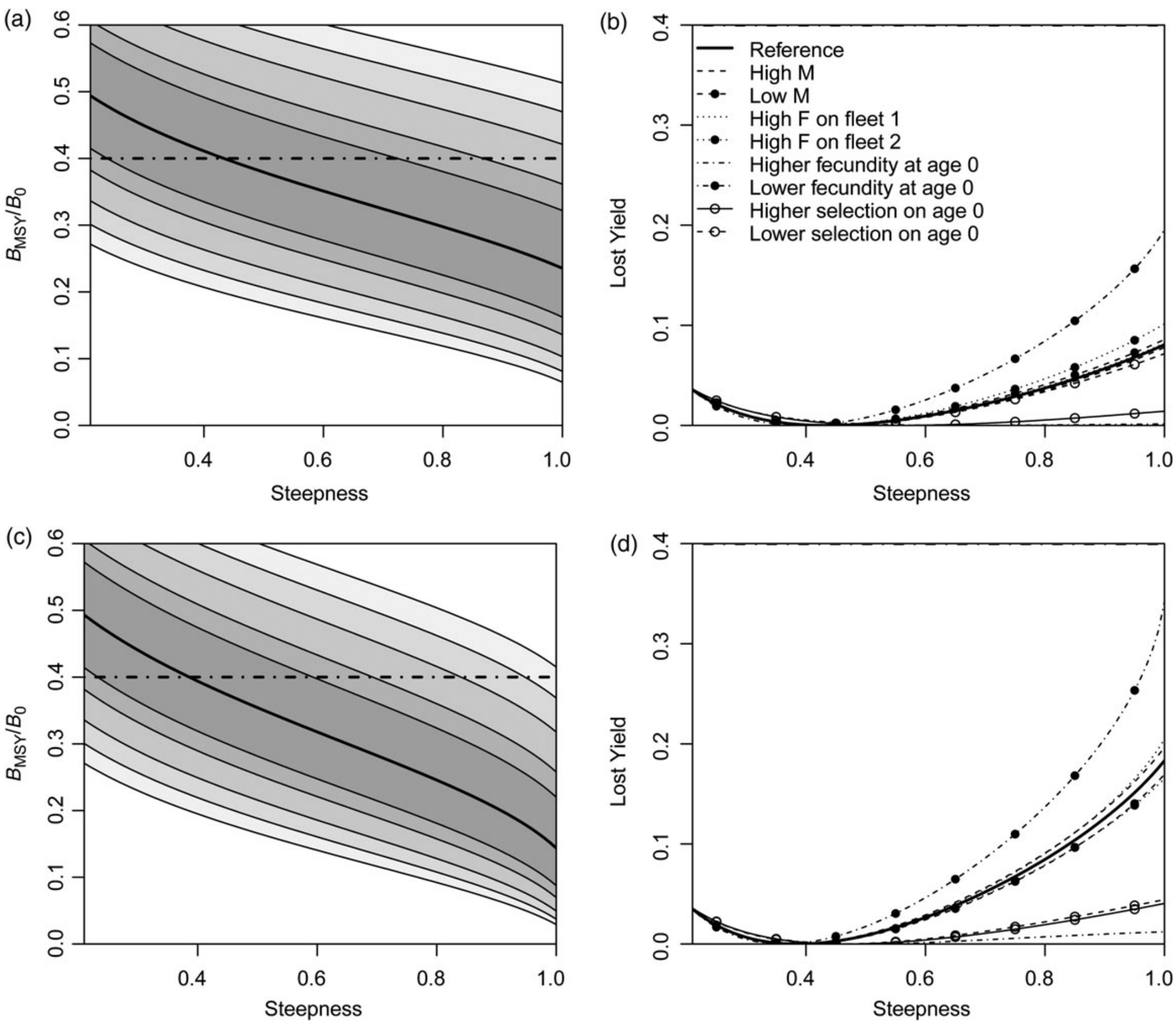

Figure 6. Yield curves (97.5, 95, 90, 85 and 80% isopleths of yield relative to MSY) versus steepness for the reference set of parameters (left panels) and lost yield versus steepness for the reference case and several sensitivity tests (right panels). Results are shown in the upper panels for blue grenadier and in the lower panels for tiger flathead.

overall compensation to a Beverton–Holt stock-recruitment relationship with a steepness of 0.65 for tiger flathead.

What can be estimated robustly?

Clark (1991, 2002) identified proxy biomass levels and harvest rates for B_{MSY}/B_0 and F_{MSY} as the levels of biomass (relative to B_0) and harvest rates (expressed in terms of a spawning potential ratio) corresponding to the minimax yield, i.e. selections so that the minimum yield over all states of nature (stock-recruitment relationships and parameters of the stock-recruitment relationship) is maximized. Figure 5 shows example yield curves for the Beverton–Holt and Ricker stock-recruitment relationship for a range of steepness values. The minimax biomass level (i.e. the biomass corresponding to the minimax yield) is roughly $0.3 \times B_0$ for the Beverton–Holt and $0.42 \times B_0$ for the Ricker stock-recruitment relationship. At these biomass levels, the sustainable yield is greater than 89% of MSY (Beverton–Holt) and 95% of MSY (Ricker) irrespective of the true value of steepness.

The minimax "estimate" of $B_{MSY}/B_{0,}$ accounting for uncertainty in the stock-recruitment relationship (Ricker and Beverton–Holt) and in steepness, is 0.33 (Figure 5). This corresponds to the lowest value of steepness for the Beverton–Holt relationship combined with the highest value of steepness for the Ricker relationship. Hilborn (2010) notes that it is possible to achieve "Pretty Good Yield" for a wide range of target biomass levels because the maximum of the yield function is achieved over a relatively wide range of relative biomass values.

Figure 6a and c show the percentiles of the yield (surplus production) curve as a function of steepness for blue grenadier and tiger flathead for the reference (or best) set of parameters for these species when the stock-recruitment relationship has the Beverton–Holt form (as shown in Figure 5, B_{MSY}/B_0 is relatively insensitive to steepness for the Ricker stock-recruitment relationship). A default choice for B_{MSY}/B_0 of 0.4 (horizontal line in Figure 6) leads to high yield irrespective of the value for steepness. This result generally extends to all of the sensitivity analyses in Figure 2 (Figure 6b and d), where the lost yield (the ratio of the yield if the stock is at a given fraction of B_0 to MSY) is $< 20\%$. The exceptions to this are when a larger fraction of the total fishing mortality is imposed by the fleet with higher selectivity on younger fish (Figure 6d and b).

The concept of lost yield can be extended to profit. Figure 7 shows the "lost profit" (the profit if the stock is at a given fraction of B_0 relative to the profit at MEY) as a function of steepness and α for the Beverton–Holt form of the stock-recruitment relationship. In contrast to the yield function, for which the region of "Pretty Good Yield" is broad (Figure 6a and c), the region of "Pretty Good Profit" is much smaller, which reflects the strong relationship between α and B_{MEY} (Figure 1b). Figure 8 shows an integrated view of both "Pretty Good Yield" and "Pretty Good Profit" by plotting the integrals under Figures 6 and 7 as a function of the target biomass relative to B_0 (essentially treating all values for steepness and α as being equally likely). In contrast to lost yield, lost profit is much more sensitive to the proxy target biomass. A range of target biomass levels from 0.45–0.63 (blue grenadier) and 0.43–0.58 (tiger flathead) leads to at least 90% of the profit integrated over steepness and α. The target biomass levels that minimize the maximum possible loss in profit are towards the upper end of the range, which maximizes average profit ($\sim 0.6 \times B_0$ for blue grenadier and $\sim 0.58 \times B_0$ for flathead).

The results in Figure 8 are based on the assumption that all values for α in the range 0–1 are equally likely. Figure 9 shows expected profit versus potential target biomass levels for the case of no information about α and when a probability distribution of $N(0.3, 0.1^2)$ is (arbitrarily) assigned to α. As expected, the average loss in profit is much lower when there is information about α, and consequently the range of target biomass levels for which the expected profit is at least 90% of the maximum possible is wider (0.33–0.60 for blue grenadier; 0.3–0.55 for tiger flathead). The reduction in the biomass level at which expected profit is maximized when this probability distribution is assigned to α is unsurprising, because lower values for α lead to lower values for B_{MEY}/B_0 (Figure 1). Although not shown in Figure 9, placing an $N(0.3, 0.1^2)$ prior on α also reduces the min-max choice for the target biomass level.

Figure 10 illustrates the sensitivity of the biomass level at which MEY is achieved to the choice of the stock-recruitment relationship

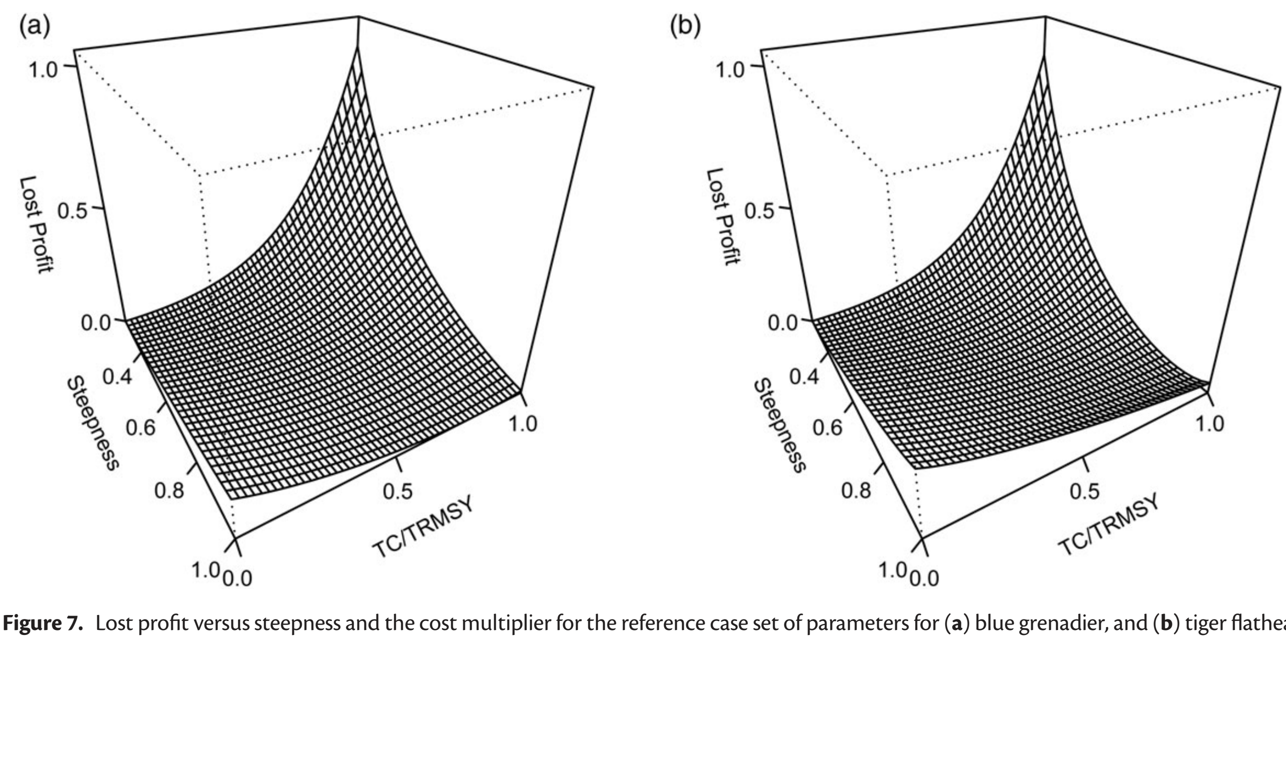

Figure 7. Lost profit versus steepness and the cost multiplier for the reference case set of parameters for (**a**) blue grenadier, and (**b**) tiger flathead.

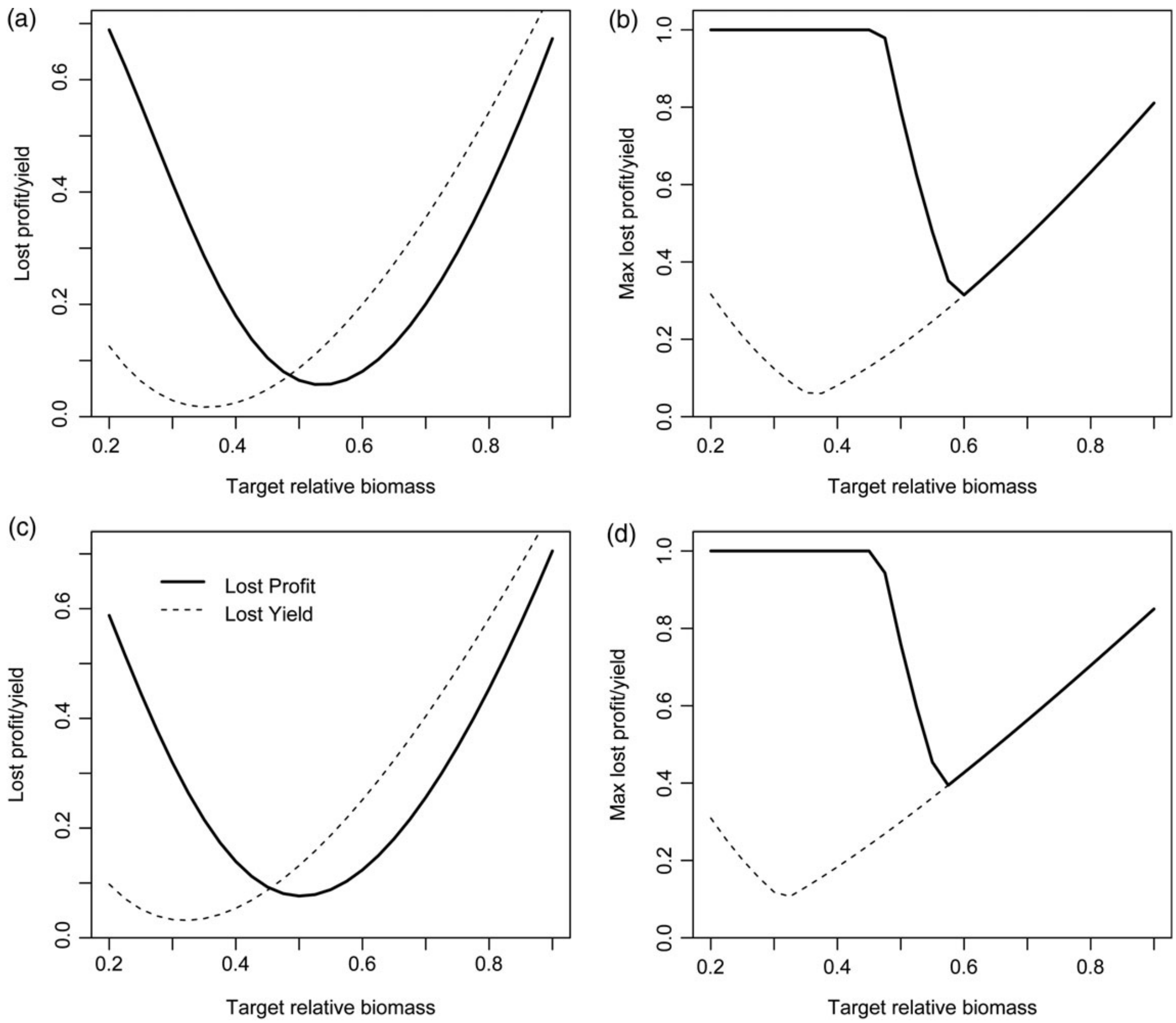

Figure 8. Lost profit (where 1 indicates that all profit is lost) and lost yield integrated over all choices for steepness and $\alpha < 1$ versus the proxy for B_{MEY} or B_{MSY} (left panels), and the maximum lost profit or lost yield over all choices for steepness and α versus the proxy for B_{MEY} or B_{MSY} (right panels). Results are shown for blue grenadier in the upper panels and for tiger flathead in the lower panels.

(Beveton–Holt, Ricker, hockey stick). The Beverton–Holt relationship implies the lowest values for B_{MEY}/B_0, while the hockey-stick stock-recruitment relationship implies target levels of 0.7 or higher are needed to minimize loss in profit. As before, the results are insensitive to the choice of life-history parameters.

Conclusion

There are good reasons for wanting to specify clear and robustly estimable targets for fisheries management. B_{MSY} is a widely used management target in many fisheries, while B_{MEY} is used in some jurisdictions (particularly in Australia). However, neither of these quantities is easily estimable in the majority of cases, whereas current depletion levels (biomass relative to carrying capacity) are generally estimable from most quantitative stock assessments (e.g. Haltuch *et al.*, 2008; He *et al.*, 2011). It appears that when the form and parameters of the stock-recruitment relationship cannot be estimated, it is reasonable to adopt depletion proxies, and that this will not lose much yield. Identifying robust proxies for targets, expressed as depletion levels, is therefore of general interest and utility in fisheries management.

Our results suggest that depletion levels in the range 0.35–0.4 would serve as a good target if the aim is to maximize yield, while depletion levels in the range 0.5–0.7 are appropriate to maximize profit when information is too poor to estimate the surplus production function reliably, as is the case for most fish and invertebrate stocks. The expected losses due to lack of information about the exact parameter values involved in the calculation of these proxy targets in these ranges are low for yield (Figures 6 and 8), but it is worth noting that the maximum losses in profit can be very high outside these ranges, and are relatively high for all choices of target biomass level. This is largely due to uncertainty in the cost multiplier α, which suggests that a modest investment in collecting economic data, particularly on costs of fishing, would be worthwhile (Figure 9). Similarly, knowing information about the steepness of the stock-recruitment relationship, e.g. from meta-analyses (Myers *et al.*, 2002) for data-poor stocks, can be used to inform target biomass levels, both those related to yield as well as to profit.

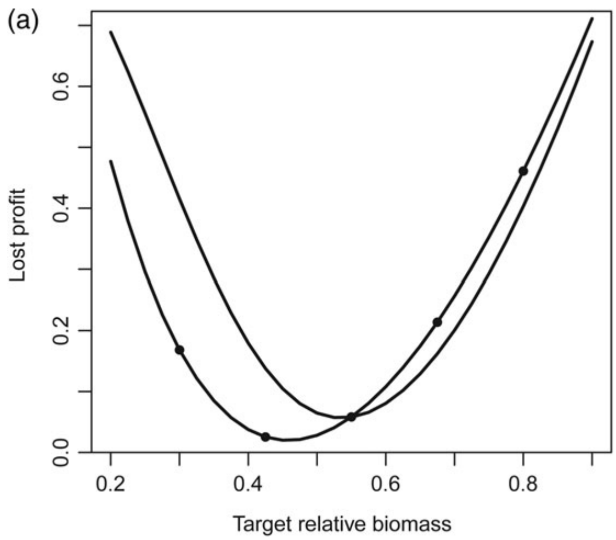

Figure 9. Lost profit (where 1 indicates that all profit is lost) integrated over all choices for steepness and $\alpha < 1$ versus the proxy for B_{MEY} for blue grenadier (**a**), and tiger flathead (**b**). Results are shown when all values for α are equally likely (lines without dots) and when α is assigned the distribution $N(0.3, 0.1^2)$ (lines with dots).

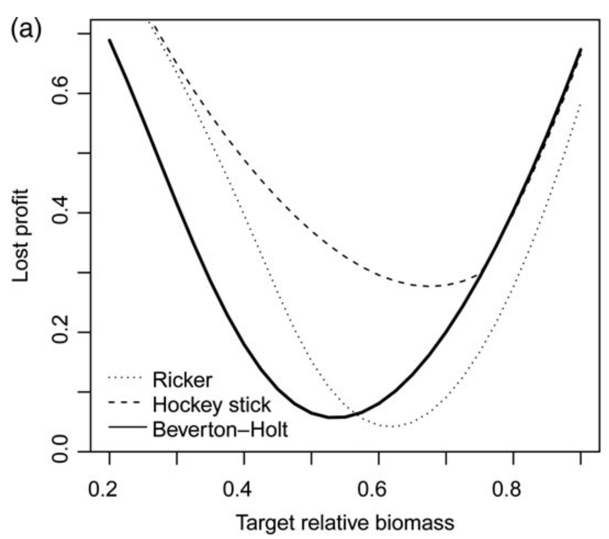

Figure 10. Sensitivity of the relationship between lost profit (where 1 indicates that all profit is lost) integrated over all choices for steepness and $\alpha < 1$ versus the proxy for B_{MEY} to the assumed form of the stock-recruitment relationship for blue grenadier (**a**), and tiger flathead (**b**), when all values of α are considered equally likely.

The analyses are based on a simplified (though commonly assumed) view of fish population dynamics and their associated fisheries. Specifically, in common with methods used for assessment purposes (such as Stock Synthesis), all of the density-dependent response to fishing is assumed expressed in the relationship between spawning biomass and subsequent recruitment. In principle, density-dependence could be assumed to relate to a different population component (such as natural mortality) (e.g. Punt, 1996). The analyses are based on the assumption of deterministic dynamics. They could be extended to allow for sources of natural variation such as interannual variation in recruitment. Clark (2002) shows that the min-max choice for B_{MSY} is larger in the face of variation in recruitment. Use of these proxy estimates of B_{MEY} and B_{MSY} rely on being able to estimate B_0. While simulation studies suggest that it is possible to estimate B_0, the conditions under which this is the case will not apply to many fisheries (e.g. those for which historical catches are unknown, for which monitoring started only recently, or for which biological parameters are not stationary). Nevertheless, the results of this paper provide default reference levels for B_{MSY}/B_0 and B_{MEY}/B_0 that can be applied given estimates of B_0.

The economic model makes several assumptions that are necessary given the data available for most fish stocks, and which will impact the selection of a target biomass level. For example, the analyses ignore the impact of supply on prices, fixed costs and non-linearities in the relationship between fishing effort and fishing mortality, and between fishing effort and fishing costs. Accounting for the first of these factors will tend to increase the proxy for B_{MEY}, as revenue will not decline as fast as catch with decreasing effort. The analyses are based on single-species considerations only. It can easily be shown (e.g. Punt *et al.*, 2011) that cpue is lower when there are technical interactions such that several target species are caught simultaneously so that costs are shared amongst species (because for example multiple species may be caught on the same trip). However, it can be difficult to allocate costs to species when multiple species are caught jointly. In principle, the entire revenue from all species caught could be used in the determination of MEY.

The analyses of this paper are focused on policies that maximize yield and profit and only consider long-term effects. However, it needs to be recognized that (i) the way a stock is managed between its current state and B_{MSY} or B_{MSY} could have major consequences for the returns to the fishing industry and the communities which depend on that industry, and (ii) some fisheries are managed (often implicitly) to achieve social objectives, including maximizing local employment and supporting lifestyle fishing. While it is beyond the scope of the present study to address either of these issues, they may be of paramount importance when management decisions are made.

Figures 8–10 contrast the different choices for B_{MSY}/B_0 and B_{MEY}/B_0 in terms of the expected lost yield/profit and the maximum lost yield/profit. These metrics effectively assume ways to address risk. They are not, however, the only metrics. For example, formal decision analysis (e.g. Thompson, 1999) could have been used to contrast the various choices. However, use of decision analysis requires developing an appropriate objective function, a task which is beyond the scope of the current paper, and which would likely differ among jurisdictions.

The results presented pertain to two "groundfish" species and can likely be generalized to other species of this type. Analyses (not shown) for orange roughy (*Hoplostethus atlanticus*) and pink ling (*Genypterus blacodes*) lead to the same results as for blue grenadier and tiger flathead. Whether the general conclusions of this study can be generalized to small pelagic species, chondrichthyans or invertebrates is a more open question, although many of the same considerations will apply. A different approach should perhaps be adopted for species with a strong functional role in the food web, such as some low trophic level species (Smith *et al.*, 2011).

Finally, B_{MSY} and B_{MEY} are included in management in several countries, as they form parts of harvest control rules (Ministry of Fisheries, 2008; Smith *et al.*, 2009; Froese *et al.*, 2011). The impact of the choice of a proxy value for B_{MSY} and B_{MEY} will depend on the form of the harvest control rule, including whether allowance is made for scientific uncertainty when setting catch limits, and will also depend on constraints imposed on the extent to which catch limits can vary from one year to the next, and other factors. The performance of harvest control rules that use the proxies discussed in this paper can be evaluated using management strategy evaluation (Smith, 1994; Butterworth and Punt, 1999).

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Appendix 1. Calculation of MSY, B_{MSY}, F_{MSY}, MEY, B_{MEY}, and F_{MEY} using an age-structured population dynamics model

Consider a fish stock that is fished by several fishing fleets (for simplicity the fisheries operate simultaneously) and is subject to age- and sex-specific (but time-invariant) natural mortality. Under the assumption of deterministic dynamics, the numbers-at-age by sex in equilibrium, N_a^s, are given by:

$$N_a^s = \begin{cases} R(\underline{F}) & \text{if } a = 0 \\ N_{a-1}^s e^{-Z_{a-1}^s} & \text{if } 1 \le a < x \\ N_{x-1}^s e^{-Z_{x-1}^s}/(1-e^{-Z_x^s}) & \text{if } a = x \end{cases} \quad \text{(A1)}$$

where $R(\underline{F})$ is the number of age-0 animals, Z_a^s is the total mortality on animals of age a and sex s. The dependence on fishing mortality is indicated in $R(\underline{F})$, but will be omitted from the remaining symbols for ease of presentation.

$$Z_a^s = M_a^s + \sum_f S_a^{s,f} F^f \quad \text{(A2)}$$

where M_a^s is the rate of natural mortality for fish of sex s and age a, $S_a^{s,f}$ is the selectivity on animals of sex s and age a by fleet f, and F^f is the fully-selected fishing mortality (i.e. $S_a^{s,f} \to 1$) for fleet f.

Age-0 abundance is modelled using either the Ricker, Beverton–Holt, or hockey stick stock-recruitment relationship, reparameterized in terms of unfished reproductive output, R_0, and the "steepness" of the stock-recruitment relationship, h (the proportion of unfished age-0 abundance expected when the total reproductive output is reduced to 20% of its unfished level), i.e:

$$R(\underline{F}) = \frac{4hR_0B/B_0}{(1-h)+(5h-1)B/B_0} \quad \text{Beverton-Holt} \quad \text{(A3a)}$$

$$R(\underline{F}) = (R_0B/B_0)e^{1.25\ln(5h)(1-B/B_0)} \quad \text{Ricker} \quad \text{(A3b)}$$

$$R(\underline{F}) = \begin{cases} R_0B/([1-h]B_0) & \text{if } B < (1-h)B_0 \\ R_0 & \text{otherwise} \end{cases} \quad \text{Hockey-stick} \quad \text{(A3c)}$$

where B is the reproductive output (the product of $R(\underline{F})$ and reproductive output-per-recruit, $\tilde{B}$):

$$\tilde{B} = \sum_a f_a \tilde{N}_a^{\text{fem}} \quad \text{(A4)}$$

where f_a is expected reproductive output for a female of age a, $\tilde{N}_a{}^s$ is the numbers-at-age-per-recruit (computed from Equation A1 with $R(\underline{F}) = 1$). B_0 is the product of R_0 and $\tilde{B}$ when fishing mortality for all fleets is zero, $\tilde{B}_0$. Substituting $R(F)\tilde{B}$ for S in Equation A3 and solving for $R(\underline{F})$ gives:

$$R(\underline{F}) = R_0\frac{4h\tilde{B}-(1-h)\tilde{B}_0}{\tilde{B}(5h-1)} \quad \text{(A5a)}$$

$$R(\underline{F}) = \frac{R_0\tilde{B}_0}{\tilde{B}}\left[1-\frac{\ln(\tilde{B}_0/\tilde{B})}{1.25\ln(5h)}\right] \quad \text{(A5b)}$$

$$R(\underline{F}) = \begin{cases} 0 & \text{if } \tilde{B} < (1-h)\tilde{B}_0 \\ R_0 & \text{otherwise} \end{cases} \quad \text{(A5c)}$$

The equilibrium catch (landings), L, for a given vector of fleet-specific fishing mortalities is:

$$L = \sum_s \sum_a \sum_f \frac{w_a^{s,f} S_a^{s,f} F^f}{Z_a^s} N_a^s (1-e^{-Z_a^s}) \quad \text{(A6)}$$

where $w_a^{s,f}$ is the mass of an animal of sex s and age a when caught by fleet f. Weight-at-age by sex differs among fleets owing to the impact of length-specific selectivity (Methot and Wetzel, 2013).

MSY occurs when L is maximized. Profit is the difference between revenue and costs, and, under the assumptions that price is independent of fleet/size/age, and fishing mortality is proportional to fishing effort, can be modelled as:

$$\pi = pL - cF \quad \text{(A7)}$$

where p denotes price-per-unit mass of fish caught, and c denotes cost-per-unit effort. Equation A7 only explicitly considers variable costs. Fixed costs are considered "sunk" for the purposes of this analysis. Dividing Equation A7 by the constant p and defining α as the ratio of total costs to total revenues at MSY, (i.e. $\alpha = c^{F}{}_{MSY}/P^{L}{}_{MSY}$) yields a quantity which is proportional to profit, but is in units of catch mass:

$$\pi/p = \tilde{\pi} = L - \alpha L_{MSY} \frac{F}{F_{MSY}} \tag{A8}$$

MEY corresponds to the $F\,(\geq 0)$ at which Equation A8 is maximized. B_{MEY} is the corresponding value for B at F_{MEY}. Note that because the focus of this paper is on equilibrium behaviour, there is no need to specify a discount rate. The optimal pathway that should be taken to reach B_{MEY} would depend on the discount rate and the initial state of the system.

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