

Combining control measures for more effective management of fisheries under uncertainty: quotas, effort limitation and protected areas

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We consider combinations of three types of control measures for the management of fisheries when the input information for policy decisions is uncertain. The methods considered include effort controls, catch quotas and area closures. We simulated a hypothetical fishery loosely based on the Icelandic cod fishery, using a simple spatially explicit dynamic model. We compared the performance with respect to conserving the resource and economic return for each type of control measure alone and in combination. In general, combining more than one type of primary direct control on fishing provides a greater buffer to uncertainty than any single form of fishery control alone. Combining catch quota control with a large closed area is a most effective system for reducing the risk of stock collapse and maintaining both short and long-term economic performance. Effort controls can also be improved by adding closed areas to the management scheme. We recommend that multiple control methods be used wherever possible and that closed areas should be used to buffer uncertainty. To be effective, these closed areas must be large and exclude all principal gears to provide real protection from fishing mortality.

Keywords: closed areas; marine protected areas; fisheries management; managing under uncertainty; effort control; quota systems

1. INTRODUCTION

There has been a substantial change in fishery policy and management over the last decade. Many states, including Iceland, Canada, New Zealand, Australia, Norway and the United States, have made significant progress in ending overfishing of stocks. This has effectively meant reducing the annual exploitation rates to below levels that are estimated to result in long-term MSY, at least on a species-by-species basis, for the important commercial stocks. In many cases, this has required the development of long-term recovery programmes to bring back fish stocks that were depleted by many years of overfishing (Murawski *et al.* 1999). In other cases, the struggle to bring fishing mortality rates under control continues (Rosenberg 2003) and many problems remain. In addition, the need to protect more than just the most important commercial species has taken on increased importance, together with the broader ecosystem level protections for habitat and non-target species. National and international law now calls for broad protection of the marine environment for fisheries, marine habitats, marine biodiversity and endangered or protected species.

Although progress has been made and the conservation and management mandate has broadened, the most basic control measures for fisheries exploitation rates are still in the form of either output controls such as quotas or input

controls in the form of limitations on effort, gear restrictions or closures of areas. The use of closed areas or marine protected areas has gained greater attention recently. In part, this has been because of the failure, in too many cases, of fisheries management to protect against severe declines or the collapse of fishery resources. In most cases where declines occurred, management by simple catch or effort controls were in place. The failure of management has usually not been because of poor scientific advice, though inaccurate estimation has occurred, but rather because control has been uncertain or the science advice has not been adhered to. Similarly, both catch and effort controls, though only used in a few cases, often suffer from implementation uncertainty, that is the inability of management to achieve the stated target because of the difficulties of fully monitoring and controlling catch and effort (Rosenberg & Brault 1993). Furthermore, in effort control-based systems increased technology investments to obtain increased efficiency (higher catchability) of the fishing vessels inevitably occurs. Few estimates of such catchability increases are available, but even in cases when the effort is not limited, it has been established that the catchability of the fleet usually increases with time (e.g. Stefansson 1998).

Protected areas address the concerns over broader ecosystem protections in some cases (Palumbi 2002; Botsford *et al.* 2003). The use of a closed area by its nature can preclude bycatch of non-target species at least within the closure, protect habitat from fishing gear damage and provide a refuge for a broad range of species in the ecosystem. In

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principle, a closed area, if it protects an area where target species are highly vulnerable to fishing effort and thereby shifts that effort to an area where the stock is less vulnerable, can also reduce the exploitation rate directly.

This paper compares, through simulation studies, fishery management through quota control, effort control and closed areas and combinations of these measures in terms of their effectiveness in achieving the basic management goals, i.e. controlling the harvest rate and conserving the resource for sustainability. As performance measures we consider the probability of stock collapse, as well as short- and long-term economic returns. Long-term economic return also reflects the sustainability of the fishery.

Some aspects of these comparisons are well known in the non-stochastic case and aspects of individual management measures are also well known in the stochastic case. Thus, for example, the effect of biological uncertainty on effectiveness of a quota system has been evaluated and found to be considerable. In part, this is inherent in the scientific foundations for fishery management in that most quotas (or TACs) are based on an estimate of the abundance of the stock in question and this is known to be uncertain. This has been studied both in general (Pope 1972) and in many specific cases (Patterson *et al.* 2001). The resulting uncertainty has been used when evaluating the performance of various quota-based harvest strategies. Such evaluations frequently consider economic concerns in addition to biological issues (Baldursson *et al.* 1996) and, sometimes extensive, evaluations include multi-species aspects (Danielsson *et al.* 1997).

It is also known that the migration rates affect the efficacy of closed areas and fleet behaviour may have a considerable effect on the efficacy of the closed areas in terms of their usefulness for protecting the resources, as detailed in Hilborn *et al.* (2004). The use of closed areas in one form or another has received considerable attention, but analysis of the biological and economic effects has been somewhat limited, though some are available. Notably, Polacheck (1990) demonstrated how closing areas could be used as a management tool and indicated the increases in spawning stock biomass likely to occur as a result, depending on migration rates.

In addition, Apostolaki *et al.* (2002) demonstrate, using simple assumptions on fleet behaviour, the benefits of a reserve depending on the redistribution of fishing effort in open areas. Whether these assumptions are appropriate will depend on economic issues such as whether fishing will remain profitable if closures are implemented. This is evident in the analysis of Hannesson (1998), which clearly shows the tendency for continued overcapacity and increased effort in the remaining open areas, leading to decreased effect of the closure, except for increasing the cost of the fishery. The present paper therefore uses a simple economic model of fleet behaviour to predict effort reallocation.

Although the different control measures have mostly been evaluated each in isolation, most real systems employ a variety of measures. It is therefore of considerable interest to formally evaluate the combinations, rather than each measure separately. This paper evaluates the effectiveness of the three types of control measures and combinations of the measures in the light of the high level of natural variation, measurement and implementation uncertainty nor-

mally present in fisheries systems. This is done using a simple underlying population dynamics model and an economic model describing the fleet dynamics. The control measures include combinations of effort control, quota control and closed areas. A closed area in this paper refers to a no-take area, sometimes termed a marine reserve, but here termed a MPA.

2. THE BIOLOGY

(a) *The population biomass*

A bulk biomass population dynamics model is used to describe changes in population levels. This is based on principles from the simplest single-area model

$$B_{t+1} = B_t + rB_t(1 - B_t/K) - Y_t, \quad (2.1)$$

where B_t denotes the biomass at the beginning of time step t (year or month) and Y_t denotes the yield in biomass during the time-step. The parameters r and K are the rate of production or increase and the carrying capacity, respectively. Unless otherwise noted, the biological yield, Y_t , is taken to be equal to the catches, which again will be equal to the landings in weight of the species in question. Thus, discards are not explicitly included in the basic model.

This model needs to be extended to account for multiple areas, variable seasonal migration, etc. Since the current model is spatially disaggregated, it will need to take into account migration, both directed migration to spawning grounds as well as feeding migrations. To describe the different types of migration, the time-step clearly has to be shorter than one full year. The obvious multi-area extension of (2.1) becomes

$$B_{t+1} = P_t^B(B_t - Y_t) + P_t^R R_{t-\tau}, \quad (2.2)$$

where B_t is the vector of biomasses by area, R_t is the vector of biomass production of each area and P_t^B, P_t^R describe the adult migration rates and dispersal of production, respectively.

The time-step will be one month, so the production (sometimes termed 'recruitment', though this is imprecise in the present context) enters every month. To link production and biomass, the components of the production vector, R_t are defined for the first month of any year (i.e. when $t = 12y + 1$) by

$$R_{A,t} = rB_{A,t}(1 - B_{A,t}/K_A).$$

For other months, $R_{A,12y+i} = R_{A,12y+1}$, $i = 2, \dots, 12$. It should be noted that r denotes monthly production rather than annual.

The rather cumbersome notation and definition is intended to reflect both body growth and recruits becoming increasingly selected within a year (requiring R_t to enter throughout the year in equation (2.2)), but of course the recruitment portion of the biomass production is determined before the start of the year.

The migration matrices, including dispersal of recruiting biomass, will be described in detail in later sections.

The delay factor, τ is used to account for recruitment delay, for example. A simple extension of this model would be to allow for a smoother transition of the production into the biomass. This could be used to approximate either a partial selection pattern or a maturity ogive. However, the current approach should capture the effect of both body

growth and recruitment entering the fishery and spawning biomass during the year rather than in a burst in January.

It is important to note that this model considers only a single species. Thus, when an effort-based system is concerned, the effect of a fleet switching from one species to another is not taken into account. Obviously, this is a major concern when using effort control as a fleet can, in principle, overfish the ecosystem one species at a time if no other measures are instigated.

(b) *Fishing mortality and harvests*

Given the short time-step, a linear version of mortality is used, so the catches are determined by removal rates

$$Y_{At} = F_{At}B_{At},$$

where F_{At} will be referred to as the 'fishing mortality', though it is strictly just a removal rate or fraction. When a distinction is needed, the terms 'fishing mortality rate' and 'removal rate' will be used.

There are, of course, limits to how large a fraction of a population can realistically be harvested. In reality, it is rare for an annual fishing mortality rate to exceed 1.2–1.5, indicating that $F_{\infty} = 0.1$ is a reasonable upper bound on monthly fishing mortality rates. In this case, the removal rate is of similar magnitude and this gives an upper bound on the fraction that can be removed within an area in a given month.

(c) *The migration model*

Migration plays an important role when considering closed areas. For a sedentary species with high larval dispersion rates one can expect that the closure of an area of sufficient size will lead to a sustainable fishery almost regardless of the fishing mortality inflicted in surrounding areas. By contrast, if the species is highly migratory in its adult stage, then closing even large areas may provide little protection in general. For a closure to work it would have to correspond with the primary area where the fishes aggregate and are vulnerable but be more widely dispersed elsewhere in the range. It is therefore intuitively likely that the effects of closed areas may be negated for high migration rates and that in this case very large areas need to be closed to obtain protection. This is seen in several analyses that have been conducted to date, e.g. Polacheck (1990) and Hannesson (1998).

The migration models require some definition of the geometry of the system, since fishes will only be assumed able to migrate between adjacent areas in the short time-step. Partly for simplification, the arrangement will be assumed to form a rectangular $n_x \times n_y$ grid with a total of $n_A = n_x n_y$ areas.

Migration is of three types in the present model, feeding and spawning migrations of adult fishes (coming together in P_t^B) and distribution of the production (in P_t^R). In any of these cases, migration can occur only between adjacent areas in any given month.

A feeding migration is in the form of a monthly dispersal coefficient, which describes the proportion that emigrates from an area in the given month. The emigration is set up to equal immigration into all adjacent regions.

Spawning migration is a directed migration towards a predefined spawning area, defined by an emigration proportion from each area, equally into each adjacent area,

which is also closer to the spawning area. When stochasticity is added, this means that the spawning migrations may take quite different routes, though they will always be in the direction of the spawning grounds. Adult migration rates are taken as either spawning migration or feeding migrations, depending on season.

The distribution of production is simply a monthly emigration proportion into adjacent areas.

In nature, migrations can be highly variable from year to year and they are also largely unknown, as seen through attempts to estimate these numbers (mainly based on tagging data) and associated uncertainty. As the number of areas increases, this problem will only become more difficult, as witnessed by several efforts in multi-species research (e.g. Anon. 2003). In stochastic simulations presented here, this is mimicked by assigning considerable uncertainty to each migration rate.

Thus, for each initial proposed migration rate, a number is first drawn from $U(0,2)$ (or, in general from $U(1-s/2, 1+s/2)$ where $s \in (0,2)$), and the migration rate is multiplied by this number. This results in a matrix, which is rescaled so that each column adds up to one again to obtain a matrix of monthly migration rates.

As noted above, the actual numbers chosen for base migration rates will considerably affect the point estimates of the effects of each type of harvest strategy. This is not the most important issue however, as it is much more important to investigate the differences in behaviour of the strategies under uncertainty.

Assuming full mixing of recruiting biomass can cause problems when negative population growth is allowed. The mixing can result in a biomass in a MPA becoming very large owing to a combination of no local fishing and high production elsewhere. The high biomass will then result in negative production. This becomes problematic if an area adjacent to the high abundance is fished very hard. In this case, the negative growth combined with mixing can produce negative stock sizes in the overfished area. The simplest 'solution' is to put the populations to zero when they otherwise would become negative but this does not capture the negative growth aspect of the production models. Hence, the approach taken is to only allow 'migration' of positive population growth and to constrain all populations to be non-negative. This approach implies that negative growth (which is partly in the form of weight loss) is a local phenomenon in the model, whereas positive growth will be distributed into adjacent areas.

(d) *Catch limitations (quotas)*

Limitations on the catches in the form of catch quotas are set according to some target or harvest control rules. Here, it will be assumed that management desires some target fishing mortality rate and hence the quota for a given month will be set to

$$Q_{Am} = f_m F_{\text{target}} B_{A,1},$$

i.e. all monthly quotas are set at the beginning of the year. For the simulations presented here, the quotas will be equally distributed throughout the year ($f_m = 1/12$). Although this may not describe a given management system, this should be similar to some real situations where larger companies distribute their allocated quota evenly

across months. To simulate a seasonal fishery a different distribution of quotas should of course be used.

Several aspects of quota systems have been evaluated in the literature. As such, systems strive to limit catches of a given species; they are in fact designed to directly limit fishing mortality of that particular species. This is in contrast to the other systems considered here since effort control and protected areas inherently affect multiple species.

By contrast, the quota system needs as input an assessment of the state of the stock. Thus, the biomass value from the assessment is used as an estimate of the true biomass and this estimate will have a high level of uncertainty. Typically, a coefficient of variation (CV) of 30% is realistic (more precisely, this is the standard error of the estimate, on log scale), though considerably higher values are sometimes seen.

Base-case stochastic simulations will therefore include a multiplicative log-normal error on the quota, from the target quota:

$$Q_t = Q_{\text{target}} e^{\varepsilon_Q},$$

where $\varepsilon_Q \sim n(0, \sigma_Q^2)$ with $\sigma_Q = 0.3$ by default. Notably this formulation will be a median-unbiased quota, but in terms of the mean, the quota will be biased upwards.

When comparing a quota system to an effort-based system, specific issues within each will be emphasized. Thus, the dependency of a quota system on a highly variable assessment has sometimes led to the use of a 'half-way rule'. Basically, this implies that management will decide on a quota which is half-way between the one suggested by the target fishing mortality and the current mortality. This methodology appears particular to a quota system since an effort or closed-area system will normally not rely on an annually highly variable assessment.

(e) *Effort limitations*

Effort limitations as modelled here simply limit the total effort expended by the fleet per time-step. The fleet is free to fish in any area. As implemented, the effort limitation will be applied each month.

In practice, an effort limitation suffers from the potential increase in catchability as vessel owners and crew strive to improve their knowledge and technology. Annual catchability increases can be *ca.* 5% p.a. in cases where effort is not limited (Stefansson 1998) and can therefore potentially be considerably higher than 5% in cases when effort control has been implemented. It follows that if effort controls are to be imposed, the annual effort will need to be reduced each year in accordance with technological improvements. It is not at all unlikely that such reductions will need to be *ca.* 10% p.a. merely to maintain a *status quo* fishing mortality rate. If true effort is to be reduced year-by-year it is therefore likely that annual reductions of 15% or more are needed in order to obtain real reductions. These considerations do not specifically take into account latent effort (due to overcapacity present in the fleet) that may creep in and become active, for example, through discarding of less efficient vessels and moving effort to more efficient vessels, or through other means. In light of these considerations, the base-case runs are all implemented under the assumption that catchability will increase by the available point estimate of 5% per year, but it should be kept in mind that

this may be an underestimate, particularly when effort is limiting.

By contrast, it is clear from assessment models that catchability is highly variable and this must be accounted for in a model evaluation of effort controls. In stochastic simulations the catchability is therefore drawn from a log-normal distribution with a high CV, resulting in variable fishing mortalities, as is to be expected from any effort-control system.

$$q_t = q_0 e^{\varepsilon_q - \sigma_q^2/2},$$

where $\sigma_q = 0.3$ by default and $\varepsilon_q \sim n(0, \sigma_q^2)$. These catchabilities and associated errors are generated for each area and time-step separately.

An effort-based system is not directed towards any individual species, but rather a generic limitation on vessel operations. In some cases, the scientific basis for setting quotas and for setting effort limitations may be different. This results when the quota is set from a biomass estimate derived primarily from research surveys using non-commercial gear, but the effort limitation is based primarily on commercial catch-per-unit-effort. Then using both quota and effort controls may buffer against uncertainty in one source of data or another.

Two cases should indicate extreme possibilities with regard to the effects of combining effort and quota control. These are on the one hand monthly independent ε_q , all independent of all ε_Q and on the other hand annual ε_q , equal to ε_Q .

One issue that separates effort controls from other measures is the initial definition of the effort to be allocated. This definition will need to be based on some model that links the effort to fishing mortality or some similar concept. This model will include some uncertainty but may include more detailed analyses than those forming the annual estimates of target effort. The approach taken here is therefore to assume that the initial effort as allocated to the fleet comes from a uniform distribution around the intended effort.

(f) *MPAs*

Area closures are modelled simply by forcing effort (and fishing mortality) in those areas to be zero. In base-case simulations, the closed areas are permanent, i.e. are true MPAs. An important part of the current work is to evaluate how generally a MPA will be beneficial in terms of management goals. Alternatives include temporary area closures. These are not considered in the present modelling exercise. Results obtained in this paper indicate that closures of small areas for a short time are very unlikely to give substantial protection to the resource and these are therefore not simulated specifically.

MPAs will have their own implementation issues, in particular monitoring and enforcement, which are not considered here. The biological uncertainty will include variable and uncertain migration rates and these are explicitly modelled.

3. FLEET BEHAVIOUR

A fundamental issue when considering MPAs and effort controls is the effect on fleet behaviour. Thus, it is well known that for a given species, protective effects of closing an area may be nullified through effort reallocation (Apos-

tolaki *et al.* 2002) and of course the decisions by the fleet will be determined by economic factors (Hannesson 1998). Here, the fleet is assumed to operate according to profit maximization. Thus, the reaction of the fleet, for example, to closures of areas, will be determined by the economic profitability of fishing in the remaining areas.

For a given time step (t) and area (A), the income to the fishery is defined as pY_{At} where p is the first sale price and Y_{At} denotes the landings. The costs are taken as κE_{At} , where E_{At} is the local monthly effort in the area. The net profit for the fishery in the given time step is therefore taken to be

$$\Pi_t = pY_{.t} - \kappa E_{.t},$$

where $E_{.t} = \sum_A E_{At}$ and $Y_{.t} = \sum_A Y_{At}$.

A base value of the multiplier κ is determined so that it provides a specified profit level, δ (e.g. 10% of income), in a reference year: $\kappa = pY_{.0}(1 - \delta)/E_{.0}$. The reference year is taken as the final historical (run-in) year, before controls are instigated. The effect of this will be that future fishing will not commence in a given area if it is not profitable, even if the management system allows such fishing.

The profit function needs to be rewritten in terms of the fleet's control variables, E_{At} . The income is directly related to monthly yields, which are related to biomass through the effort,

$$Y_{At} = F_{At}B_{At} = q_{At}E_{At}B_{At}.$$

Hence the profit function to be maximized is of the form

$$\Pi_t = \sum_A c_{At}E_{At},$$

where $c_{At} = (pq_{At}B_{At} - \kappa)$.

The economic model assumes that the fleet will maximize its own economic gain under the constraints given by quota limitations, effort controls and closed areas. The fleet has the control variables $\mathbf{x} := (E_1, \dots, E_{n_A})'$, denoting the effort that can be allocated to each area within the given month. For a given effort, the corresponding fishing mortality is $F = qE$ (ignoring subscripts) so the predicted catch can be given in term of effort *viz.* $Y = FB = qEB$.

This leads to the following linear programming problem, to be solved for each time-step in the model:

$$\begin{aligned} \max_x \quad & c'x := c_1E_1 + \dots + c_{n_A}E_{n_A} \\ \text{w.r.t. (a.1)} \quad & a'_1x := E_1 + \dots + E_{n_A} \leq E \\ \text{and (a.2)} \quad & a'_2x := (q_1B_1)E_1 + \dots + (q_{n_A}B_{n_A})E_{n_A} \leq Q \\ \text{and (a.3)} \quad & a'_{3A}x := q_A E_A \leq F_{\infty}, A = 1, \dots, n_A \\ \text{and (a.4)} \quad & a'_4x := E_{A1} + \dots + E_{Ap} \leq 0 \\ \text{and (a.5)} \quad & a_{5i}x := E_i \geq 0, i = 1, \dots, n_A, \end{aligned} \quad (2.2)$$

where the first constraints enforce effort restrictions, the second (a.2) and third (a.3) sets of constraints enforce the upper bounds on removals as tonnes and rates in each region, with the upper bound set to infinity if a constraint is not used. Finally, the constraint (a.4) enforces a closure of areas if necessary. It should be noted that there is no non-linearity in the cost function as local biomass goes down. Further, there is no difference in net profit by fishing in two areas of equal abundance, whether the total catch is taken equally in both or only in one area (notably though, the time period is short).

The above model will take into account most of the primary economic issues, e.g. fishing will only take place in areas where fishing is profitable. Even if the various bounds are relaxed, the model will not allocate effort to areas where fishing is not profitable. Thus it must be noted that in some real situations where fishing is not profitable but commences nevertheless (e.g. due to subsidies or due to behaviour otherwise not determined due to profit alone), a different profit function should be used to predict fleet behaviour.

The constraints in the model explicitly take into account each of the limitations implied by quota control, effort control or closed areas or any combination of these. However, the economic model operates on top of the constraints. For example, even when a quota is set according to some target, it may not be taken if the biomass is so low that the fishery can not be run at a profit.

The decisions made by the fleet thus optimise the monthly net returns and do not take into account future or historical prospects. As for all linear programming models, resources are allocated in accordance with vertices of the solution space. It follows that the resulting linear programming problem gives solutions that may jump from one area to another in different time steps ('bang-bang' solutions). The results are, however, summed across several months and areas, yielding a smoother overall outcome. In principle, nonlinearity could be introduced to alleviate this, but the corresponding elasticity (e.g. the power in a power function relating catch per unit effort to abundance) would be somewhat arbitrarily chosen since the power is poorly determined (D. S. Butterworth, personal communication, in Stefansson 1992). Instead, only a bound is set on the possible fishing mortality rates in any time period in any area. Total effort as used in the cost function is of course the sum across areas of local effort, and in the model it is beneficial for the fleet to fish harder in areas of greater abundance, as would be expected in real situations. However, unlike simple biologically based models, the one presented will ensure that fishing does not continue in areas where it is not profitable. A result of the 'bang-bang' behaviour is that fishing may occur in a single area in a given month since this is the area of the highest abundance. If this results in depletion, the fleet may, in the following month, move completely to another area. Hence, although it is clear that this can be only a partial reflection of reality, it should be considerably closer than not taking any fleet behaviour into account or assuming some fixed switching scheme.

Another aspect not modelled is the distance to the various areas. In some real cases, this will affect the decisions made, as the costs will go up for distant areas. The distances to and between areas are crucially dependent on the geometry of the region. Since they are potentially important, such assumptions should be considered when applying combinations of controls of a specific case.

4. MANAGEMENT OBJECTIVES

Many fishery management schemes suffer from a lack of formal objectives to be maximized. However, several conflicting objectives often exist. These include increasing biological and economic yields, reducing the probability of

overexploitation and preventing the depletion of the resource to a point where fishing is not sustainable.

The economic yields will be evaluated using net present value using an annual interest rate of 2% (monthly rate of 2/12%). The net present value is based on annual totals.

Fishing mortality targets will be used for quota decisions within the model. When the quota is not to be limiting this target is simply set very large. The target can also be set at key biological reference points such as F_{MSY} , $\frac{1}{2}F_{MSY}$ and at $F_{collapse}$. These are defined as the fishing mortality rate that is expected to result in the maximum sustainable yield, half of the previous quantity and the fishing mortality rate expected to result in collapse of the stock, respectively. Fishery controls with implied (but possibly not intended) targets close to some of these have been observed in real fisheries. In particular, in addition to the case where there truly is no formal bound on the catch, some fisheries have apparently operated for extended periods at realized fishing mortality rates near the estimated collapse fishing mortality rate, in spite of attempts by management to do otherwise (e.g. Cook *et al.* 1997).

Using $\frac{1}{2}F_{MSY}$ may not appear to be an economically sensible decision, but this corresponds to a fishing mortality reduced from another biological target (F_{MSY}), usually to account for uncertainty and bias in assessments and also sometimes to account for a desire to move from a biological maximum in the general direction of an economically optimum yield. A 30% level of uncertainty alone implies that F_{target} may need to be considerably reduced from F_{MSY} , if the annual F is to stay below $F_{collapse}$ with high probability and below F_{MSY} with at least 50% probability, as stated in some binding international agreements such as the UN Treaty on Straddling Fish Stocks and Highly Migratory Fish Stocks.

5. BASE RUN SETTINGS AND OUTPUT DEFINITIONS

The geometry of the region is important. The default case is a 3×3 grid with a spawning area in one 'corner' of the region and the remaining grid cells designated feeding areas, laid out as in table 1. This simple set-up captures some of the required details such as the difference between adjacent and non-adjacent areas, etc.

Table 2 gives the default settings of each biological model component.

Table 3 gives the default settings of each component of the model for the fishery. For the economic model, a fixed annual interest rate of 2% is used. The cost of effort is based on assuming baseline profits to be 10% in the last simulation year and the price per kilogram landed is taken to be \$1.

In order to obtain a consistent spatial population structure in the initial simulation years, the simulations start at a much earlier time point. The basic simulation background is an overexploitation scenario.

Thus, the default history starts with an initial biomass level, $B_0 = 500$ and proceeds with an overfishing situation ($F = 0.8$, $F_{collapse} = 0.4$) for 50 years. Since the historical fishery is based on the same fleet and population dynamics as the simulations, the historical unit price is simply set high and costs low enough so as to ensure that the fishery continues at the historically low levels of abundance.

Table 1. Area definitions, based on 3×3 grid. Areas 1,2, 4,5 are taken as spawning areas.

1	2	3
4	5	6
7	8	9

Table 2. Default settings for biological parameters.

component	value	uncertainty model
number of areas (n_A)	9	log-normal, CV = 0.5
r in each area	0.5 per year	
K in each area	$2500/n_A$	
biomass	$rB(1-B/K)$	
production (recruitment)		
homing	0.2	uniform
migration rate		
feeding	0.2	uniform
migration rate		
recruitment (production)	0.2	uniform
migration rate		
recruitment (production)	36 months	
delay		

Table 3. Default settings for fleet parameters.

component	value	uncertainty model
baseline effort allocation	correct	uniform
catchability	1	log-normal, CV = 0.3
quota	biased	log-normal
maximum monthly	0.1	
fishing mortality		
collapse fishing mortality (annual)	$F_{collapse} = r = 0.5$	

Several named quantities are used in output tables and plots. The primary quantities are short- and long-term economic yield and collapse probability.

A stock collapse in a simulation is defined as the event when the stock goes below $K/4$ in any year, or (if the stock starts out below $K/4$) the stock goes below the starting value. This corresponds to defining B_{lim} as the smaller of $K/4$ and B_0 and computing the probability of ever declining below B_{lim} .

The short-term economic yield is the net present value of the profit stream, Π_t , for the first 15 years of simulations. A default number of 50 simulations is undertaken for each scenario considered.

To compute the long-term (infinite horizon) economic yield, the short-term yield is added to the value of final biomass. The latter is based on taking the sustainable yield at the final biomass level in each area, which is used to compute a corresponding removal rate. This implies a certain annual profit if the populations are maintained at this biomass *ad infinitum*. The net present value of this profit

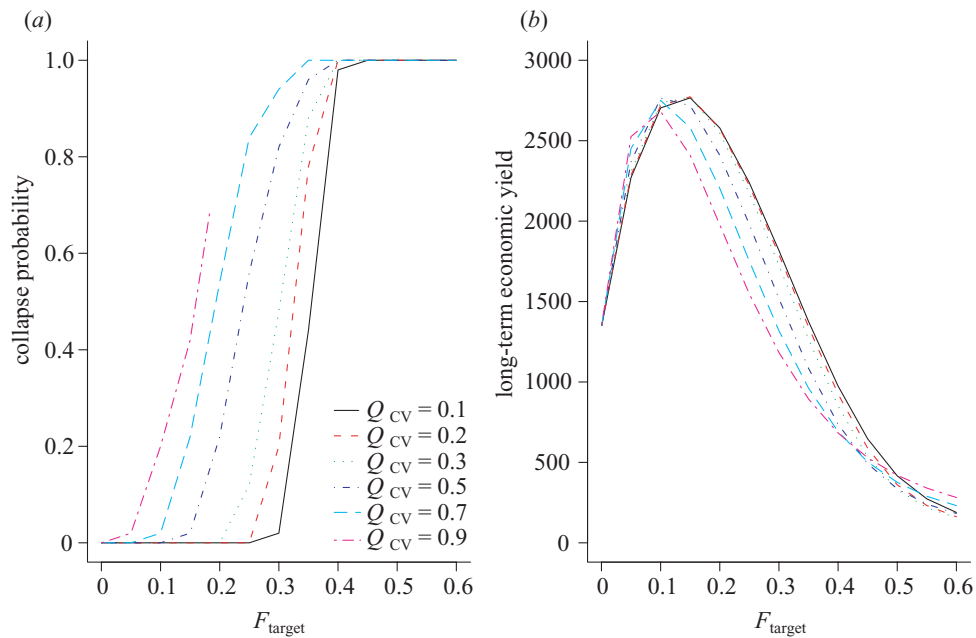


Figure 1. Quota control only. Probability of (a) stock collapse and (b) long-term economic yield as a function of target fishing mortality for different levels of uncertainty (CV) in the quota.

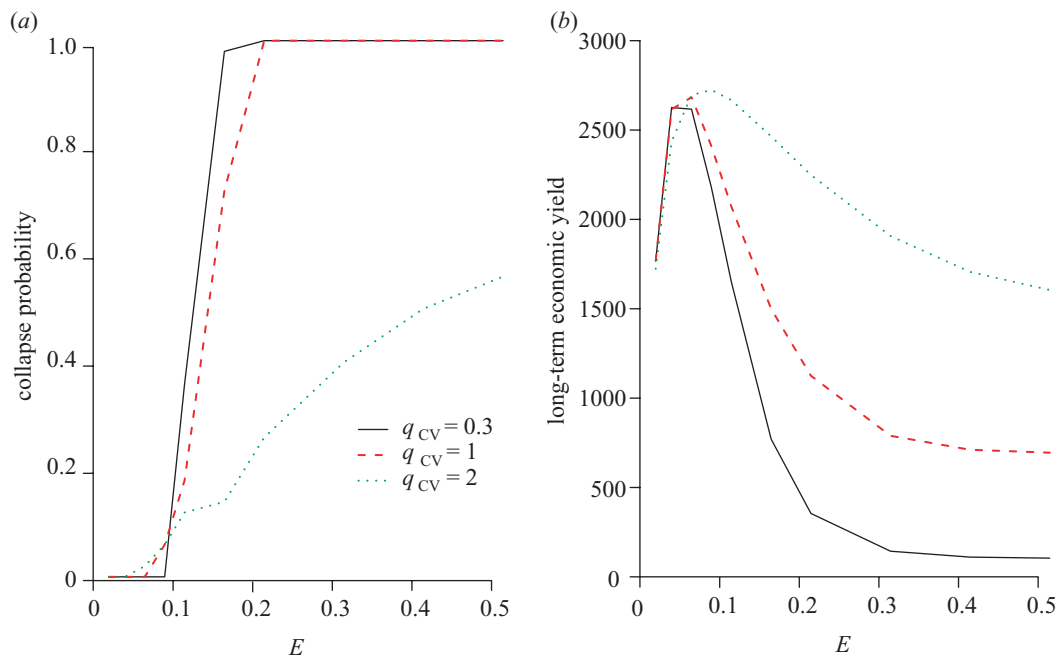


Figure 2. Probability of (a) stock collapse and (b) long-term economic yield versus target effort for different levels of uncertainty when using effort control alone.

stream is taken as the value of the resource. This approach ignores the effects of migration in the long-term and is an evaluation of the price of each locally sustained biomass.

6. SIMULATION MODEL RESULTS

(a) Quota control alone

For a fishery that is controlled by a quota alone, the pattern in yield and economic return is well established. Figure 1 shows the effect of target fishing mortality on long-term profit, for different values of quota uncertainty. Every case

shows the traditional curve of yield as a function of fishing mortality. Similar results are obtained for short-term (15 year) profits, though in this case the losses at low fishing mortality become more apparent.

The implementation of a quota in the real world is never exact in the sense that the estimate of the quota to achieve a particular fishing mortality rate, the estimated reference level of fishing mortality and the ability to control the fee so exactly that quota and no more or less is caught (including discards) are imperfect.

Therefore, it is important to consider the interaction between the target fishing mortality underlying the quota system and the uncertainty in implementing the correct quota in the absence of large closed areas.

The effects of increased uncertainty are not the same at low and high fishing mortality. Increased uncertainty at low fishing mortality rates, i.e. when the stock is underused, has the effect of increasing profits by allowing higher exploitation than the target rate from time to time. The effects are not symmetric since the log-normal errors occasionally give very high values which result in higher catches. At higher levels of target fishing mortality the converse effect may occur. Overestimating stock abundance when the target fishing mortality rate is high will result in setting a quota too high and depleting the stock with longer-term impacts. The log-normal errors mean that sometimes the overestimation will be severe and the consequences in terms of the stock are severe. But with a high target fishing mortality rate, underestimates will only have a short-term benefit in terms of conserving the resource.

(b) *Effort control alone*

A system based on only effort control behaves very similarly to a quota control system if uncertainty is low. Both systems depend upon an estimated target fishing mortality to set control parameters. If the target fishing mortality rate is achieved with reasonable precision the results will, from a biological viewpoint, be the same whether catch or effort is the primary control parameter. Considering the inherent uncertainties in implementing quota and effort control systems is likely to lead to some differences however. In particular, effort control systems rely on selecting some unit of effort, such as a vessel day fishing or horsepower days, that can be considered constant in terms of the fishing mortality inflicted on the resource per unit of effort.

Unfortunately, fishing power can be increased by many different attributes of fishing vessels including vessel power, gear modifications, instrumentation and so on. For these simulations the effort control system is modelled such that there is drift (annual increases) in catchabilities, here set at 5%. In real situations, this drift would be associated with investments and a corresponding cost. The additional investment cost is not included in the economic model here.

The initial effort allocation is assumed to refer to a measure of target fishing mortality. Uncertainty is included by drawing the true reference effort from $U(0.75E; 1.25E)$, so the reference effort will correspond to a fishing mortality in the range 75–125% of the intended mortality.

The unimodal shape seen in figure 2 is of the same general shape as is commonly seen when fishing mortality is placed on the x -axis. It must be recalled that at high levels of ‘target’ effort, the economics will ‘kick in’ and as the stock goes down, eventually the fishery will close automatically since the costs will be too high. Interestingly, however, these simulations indicate that at high levels of target effort, increases in uncertainty may be beneficial. Although not obvious at the outset, this may be owing to uncertainty allowing occasional use under the target, giving some economic benefit in the longer run.

(c) *MPA control alone*

The ‘amount’ closed or ‘protected biomass’ will be defined as the initial proportion of biomass (B_{safe}) within the MPA. Depending on the local abundance, a given biomass closure may have many or few closed areas and several combinations of closed areas may give similar levels of protection. Similarly, closing juvenile areas will not give the same results as closing a spawning area. Consequently, there will usually not be a simple function describing economic outputs or collapse probability in relation to the biomass protection. Therefore, the figures below need to be interpreted using a broad-brush approach.

Figure 3 gives pairwise scatterplots of the main results when using only closed areas as a management tool.

Economic yield increases as a function of the protected biomass, until almost all is closed, when it decreases drastically. However, long-term economic yield increases monotonically as a function of the protected biomass, since the value of the final biomass more than offsets the lack in shorter-term catches.

Naturally, it may not be feasible in real situations to protect such large proportions of the biomass. In this case, however, it is important to realize that ‘feasible’ closures may not necessarily provide the protection benefits that might be sought from an MPA strategy used as the primary management control. If a large fraction of the stock is not protected from fishing throughout the year by the closed area, then the MPA will be much less effective. For the target species, it is not the size of the area that matters but the distribution pattern of the fish with respect to the closed area. Of course, the ancillary benefits of an MPA such as protecting habitat from disturbance or destruction or reducing bycatch of non-target species distributed within the closure should be considered as well when MPAs are designed.

For the stock simulated here, so as to start reducing the probability of falling below the biomass threshold, over 60% of the initial biomass needs to be protected.

On average, for each scenario in figure 3, the final biomass does not increase significantly above the MSY level and hence the final value of the resource does not fall again.

This would occur if protection was for a sufficiently long time that the abundance developed towards carrying capacity and density-dependent population processes were operating. Since long-term economic yield is based on the value of the resource into the future, this value does not drop even if very large protected areas are implemented because the resource has not ‘lost’ value.

The conclusion from this analysis is that to obtain a rebuilding of the stock without any other controls, a very large percentage of the biomass needs to be protected. This is reasonable since, so as to obtain, for example, a 20% exploitation rate, a protection of 80% of the biomass will be needed if no other controls are used.

Note, however, that this does not equate to closing 80% of the range of the stock unless fishes are evenly distributed throughout the range.

This pattern appears to hold over a wide range of migration patterns, though the details vary of course. Migration pattern changes primarily affect the choice of areas to be closed to achieve a given level of protection. Migration does not eliminate the effectiveness of MPAs as a tool, assuming they are well designed.

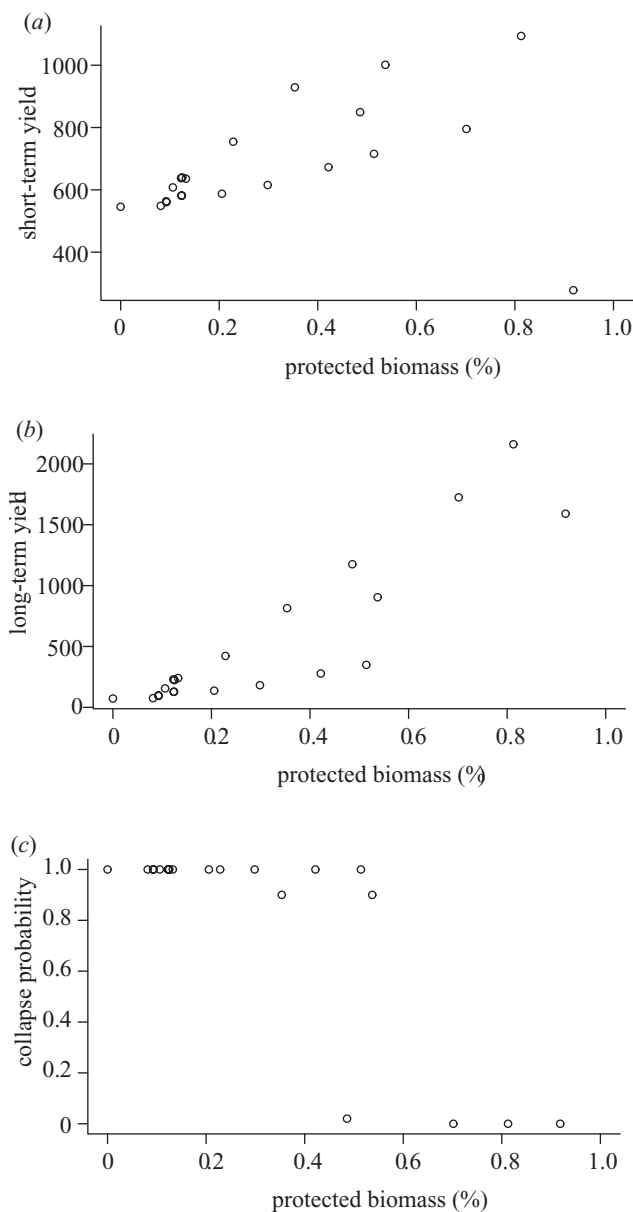


Figure 3. Effect of controls using only permanently closed areas, linking (a) short-term (15 year) economic yield, (b) long-term economic yield and (c) collapse probability with the initial proportion of biomass within closed areas. Default feeding migration rate, 20% emigration from each area to adjacent areas.

In these simulations, closures of 50% or more of the area always increase long-term economic yield. The full effects do depend on the migration rates somewhat. If there is no feeding migration, then there is no added gain in closing too much. For moderate to high rates, there is steadily increasing long-term gain in increasing the size of the closed area.

7. COMPARING CONTROL SYSTEMS

The various control systems considered here are difficult to compare directly. Each will allow some fishing mortality on the stock as a whole and each will have consequences, both in terms of economics and of sustainability. Extracting from each method the inflicted fishing mortality rate (i.e. the fishing mortality actually experienced by the stock) and

calculating economic consequences provides a common basis for comparing the methods. Figure 4 illustrates that there is a considerable difference in how the methods perform.

Notably, a properly implemented quota system (i.e. one that achieves its goals of moderate exploitation) appears to give much higher profits for a given fishing mortality than a system based on closed areas alone. This is in line with earlier results (e.g. Hannesson 1998) and is a rather obvious consequence of the fact that uncontrolled fishing in a sub-area at high local fishing mortality will be much more costly than fishing at a low fishing mortality in the entire area.

By contrast, if there are problems with implementation of the quota or effort system, then the resultant fishing mortality rate will be higher than intended. In this case, a closed area may be able to better control fishing mortality and therefore achieve greater economic yield in the long-term. For example, if the fishing mortality rate should be 0.25, but a quota or effort control system alone allows the rate to be closer to 0.4 then a well implemented closed area strategy can result in much higher economic return.

Examples of quota systems that fail to achieve their targets abound, and include several species, including cod (*Gadus morhua*), in the North Sea (Cook *et al.* 1997), as well as cod off Newfoundland (Hutchins & Myers 1994) and in Icelandic waters. In the case of the Icelandic fishery, a formal harvest rule was defined and largely adhered to, but assessment problems led to the realized fishing mortality being almost double the target proposed and implemented (Danielsson *et al.* 1997).

Of course, a closed area system is not immune to imperfections in implementation either. Closing areas that are misplaced or are too small, or are only closed for a part of the year such that fishing mortality during the open times can easily compensate for the closed period can undermine effectiveness.

8. COMBINING METHODS OF CONTROL

Although the basic assessment information used to choose a target fishing mortality rate is the same for any control strategy this does not mean that the effects of uncertainty will be the same. This is because different methods of control are based on different sources of information and have different sources of uncertainty. For example, quota systems rely on an assessment estimate of fishing mortality rates and biomass, whereas a closed area strategy relies on information on distribution and relative abundance. Effort control systems rely on effort data and estimates of catchability from assessments. In addition, the implementation uncertainty for each method relies on the ability of the management authority to control catch, effort or exclude vessels from particular areas effectively. These uncertainties are unlikely to be the same in practice. Combinations of control methods may therefore provide a means of buffering against uncertainty and protecting long-term benefits from the resource.

In practice, more than one method is often used for control of a fishery. Examples include management of groundfish in New England through effort control and closed areas, the Alaska groundfish fishery managed through quotas and closed areas, and the recent recovery plan for North Sea cod managed through a combination of quota and effort controls.

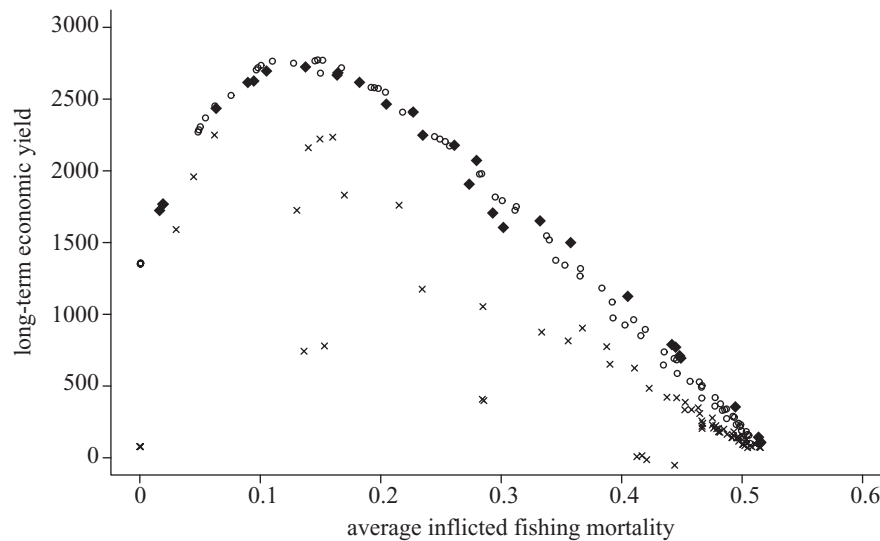


Figure 4. Comparing individual control systems used in isolation in terms of average inflicted fishing mortality rate and long-term yield. Open circles denote a quota-based system, filled diamonds denote an effort-based system and crosses denote closed areas alone.

Here, we focus on combinations of the three methods we have simulated.

To examine combinations of quota control and MPAs the quota was set according to a target fishing mortality rate. A sequence of five MPA scenarios are used (table 4), representing partial or full closures of feeding or spawning grounds, with a sample presented as plotted output.

The probability of stock collapse is strictly increasing as a function of the target fishing mortality if no other measures are undertaken. Figure 5 shows the combined effects of quota control and closed areas in terms of collapse probability, for a fixed level of uncertainty within the quota system. The initial protected biomass levels shown in figure 5 are a selection to illustrate the effects of a range of protection levels.

If low fishing mortality is maintained through quota control, then there is little risk of stock collapse. In the case of higher values of target fishing mortality, if an MPA is implemented, the risk of stock collapse can be greatly reduced. In effect, the uncertainty in quota control is buffered by the MPA and the buffering effect is related to the size of the closure although the degree of buffering also varies depending on which precise areas are kept closed, owing to migration, spawning behaviour and fleet behaviour. It is seen that the result in figure 5 translates into buffering the risk to long-term economic yield too.

A very similar effect occurs if an MPA is added to an effort control system. Again, the buffering against uncertainty observed in figure 6 occurs because the methods have a different basis. The risk of collapse is lowered and long-term yield is protected by the inclusion of an MPA.

Protecting a large fraction of the stock ensures the long-term yield because of the lower risk of overfishing and stock declines owing to uncertainty in setting the quota, as seen in detail in figure 7, for various levels of uncertainty.

The buffering of uncertainty by an MPA is evident when collapse probability, short-term and long-term economic yield are compared for a given fishing mortality rate target with different levels of uncertainty in implementation. When the fishing mortality rate target is relatively low and

uncertainty is low, long-term yield can be maintained even with few or no closed areas because the collapse probability is low. When the collapse probability increases, either because the mortality target is high or because of uncertainty, yields are reduced. The addition of a substantial MPA allows long-term yield to be maintained by reducing the probability of stock declines and collapse.

Combining quota control with effort control also seems to improve the management system by reducing the risk of stock declines. In the simulations here, this effect is apparent for both short-term and long-term economic yield (figure 8). Effectively, one management system provides a backstop for the other. For example, in a poorly managed quota system where the target removal rate may become quite high, an effort limitation will alleviate some of the problem, leading to a considerably higher short-term (15 year) profit. This effect is of course more pronounced in the long-term case, where the profits over an infinite horizon drop more severely as the target fishing mortality increases and the added effort limitations are therefore even more important. The ability to avoid declines increases as the strength of the control of effort or the size of closed areas, in terms of the proportion of the biomass protected, increases. From these simulations, the complementary measure, either effort restriction or closed areas should be quite restrictive to obtain full benefit. Little in the way of economic yield is lost but substantial buffering against underestimating or exceeding the quota is obtained.

In these combinations of quota and effort systems, the problems inherent in both approaches have been explicitly modelled. Thus, there is a built-in catchability increase in the effort system and the quota is implemented using a halfway rule.

9. DISCUSSION

All methods of management are prone to errors. The sources of these errors include implementation problems or measurement errors. In many cases, these problems are serious enough that a single enforcement system, such as a quota-based system, is not enough to ensure a sustainable

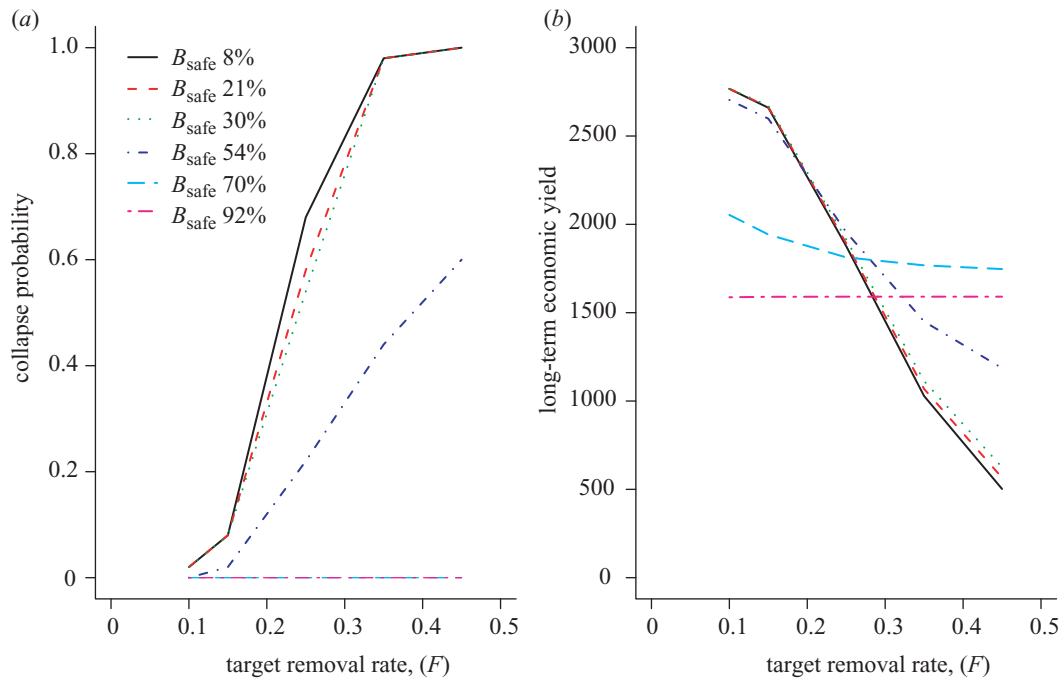


Figure 5. Effect of quota control and closed areas on probability of (a) stock collapse and (b) long-term yield. CV in quota fixed at 0.6. The x-axis indicates the target removal rate for the quota control whereas each line type corresponds to a fraction of protected biomass (B_{safe}).

Table 4. MPA scenarios considered in simulation output.

area(S)	protected biomass (B_{safe})(%)	description
9	8	minimal closure
8,9	21	part of feeding grounds
7,8,9	30	half of the feeding grounds
1,2,3,6,7	54	parts of spawning and feeding grounds
1,2,3,4,5,6	70	spawning closure and part of feeding grounds
1–8	92	very extensive closure

fishery. An obvious conclusion from the simulations presented is that the risk of stock collapse can be considerably reduced by adding closed areas to a problematic quota system (e.g. figure 5). A further conclusion is that minor closures have little effect and if MPAs are to be used on their own very large areas need to be closed to fishing.

If combined systems are to be applied in real situations, issues not addressed in this paper will no doubt arise. If a quota system is to be combined with effort limitations, then simulation results would indicate that each target could be separately set at a reasonable level. The negative effects of deviations in either restriction would then be dampened by the other. Although somewhat speculative, it would seem likely that compliance issues in either system will be somewhat alleviated if there is also a second limitation. Thus, a tendency for illegal landings within a quota system might be automatically reduced if the number of days at sea is also limiting.

The results presented in this paper highlight several areas of future work. A plausible argument for MPAs is the potential side effect of increased productivity within the reserve. This effect may be more than simply a result of population increase, e.g. owing to less disturbance or greater benthic food supply. Basically, this corresponds to a local increase in r , the intrinsic rate of increase for a population, and would enhance any benefits shown from the simulations presented when combining MPAs with effort or quota systems.

For a given case study, it would be possible to devise specific definitions of regions and possibly also of migration patterns, to draw case-specific conclusions. Care must be taken, however, not to use point estimates of migration rates, etc., but ensure that uncertainty is taken into account. This implies that a certain minimal level of generality is maintained, even in specific cases.

The present paper has not considered multi-species or technical interactions. These are important since they do not interact in the same manner with all control measures. MPAs and effort controls are inherently multi-species management measures, while a quota obviously focuses control on an individual species. MPAs will tend to have broader impacts because they specifically protect habitat if sited properly. In the context of quota or effort systems, it is clear that technical and species interactions will amplify the benefits of combined control measures, particularly if an MPA is included, but a quantification of this effect would be useful.

Our results stem primarily from the buffering effect one management measure has against errors in the implementation of an accompanying measure. In practice, this buffering may result when the basis for the methods is different such that different sources of uncertainty come into play. For example, MPAs may be designed based on relative

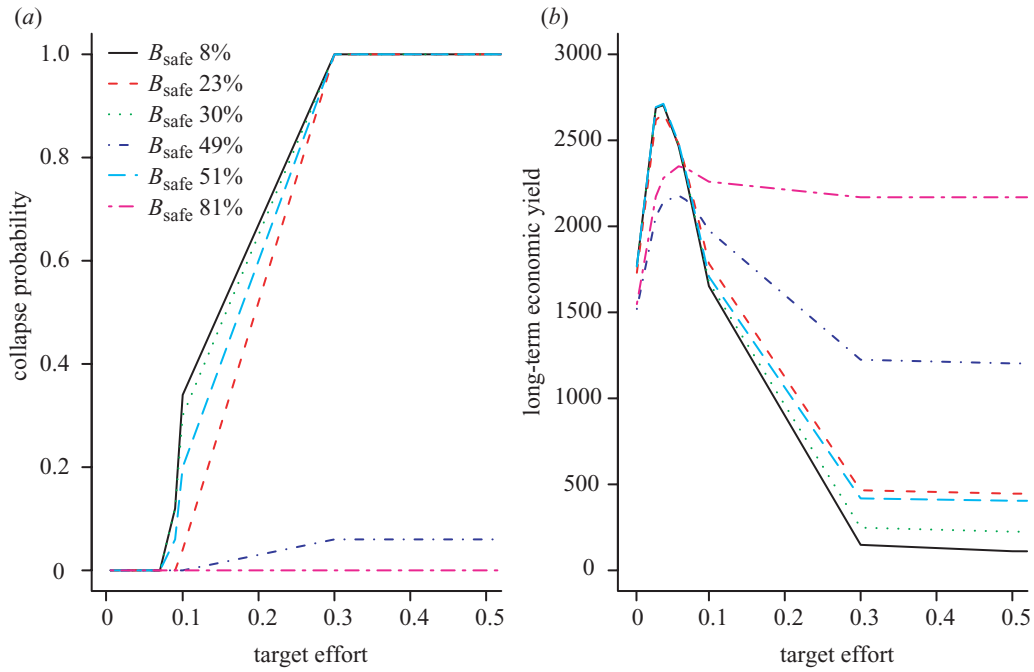


Figure 6. Effect of effort control and closed areas on (a) probability of stock collapse and (b) long-term yield. The x-axis indicates the target effort for the effort control whereas each line type corresponds to a fraction of protected biomass (B_{safe}).

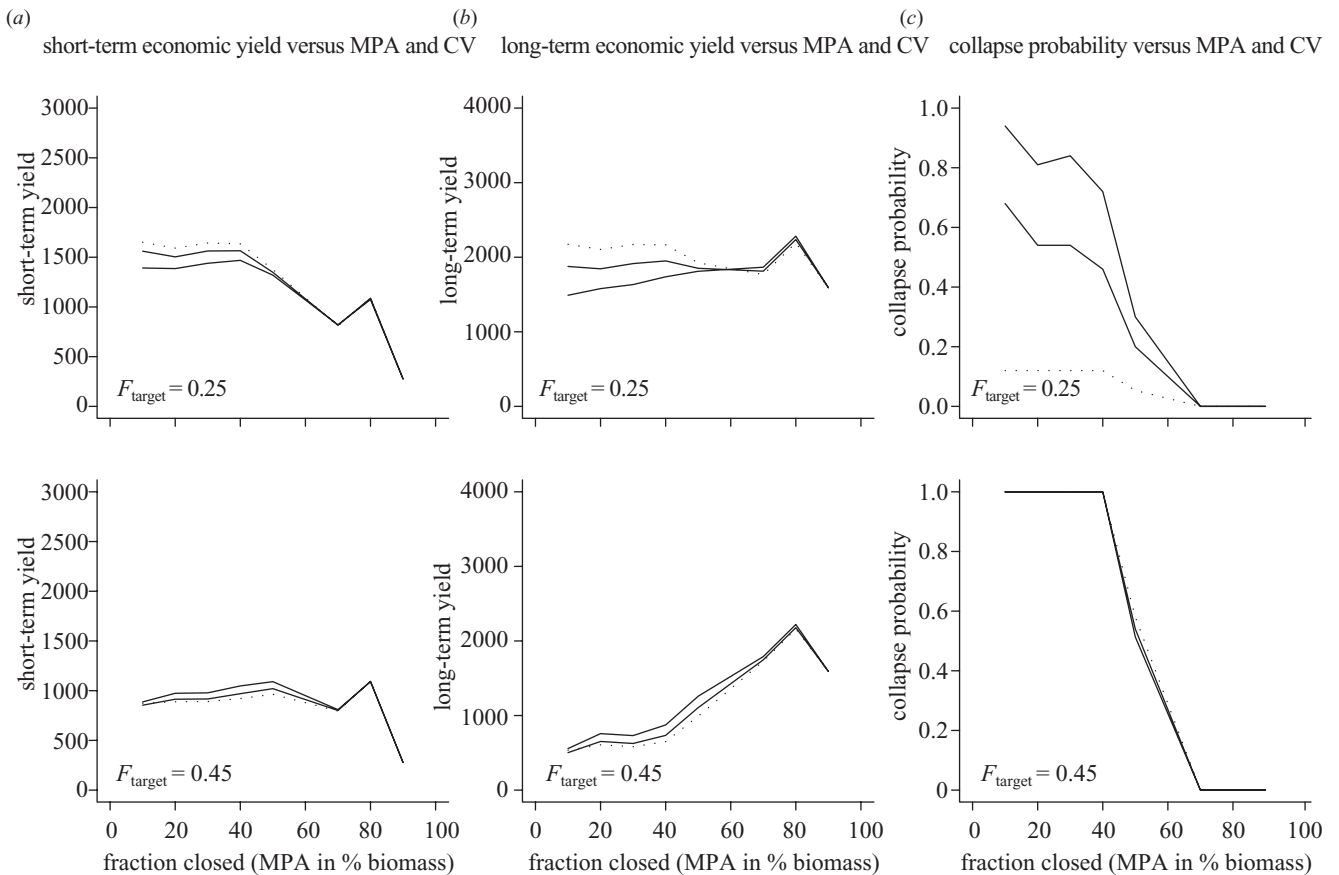


Figure 7. Q and MPA control. Economic yield and collapse probability as uncertainty and closures vary. $Q_{CV} = 30$, dashed line; $Q_{CV} = 60$, solid line; $Q_{CV} = 100$, dotted line).

abundance and distribution data or the distribution of fishing effort. Quotas may be set primarily based on research survey trends and total catches. The errors in one type of data and analysis may be mitigated by the other types of

data and analysis providing a greater buffer against uncertainty. This implies that as many sources of information as possible should be used, but perhaps not combined devising a single control measure. Additionally, the basis for

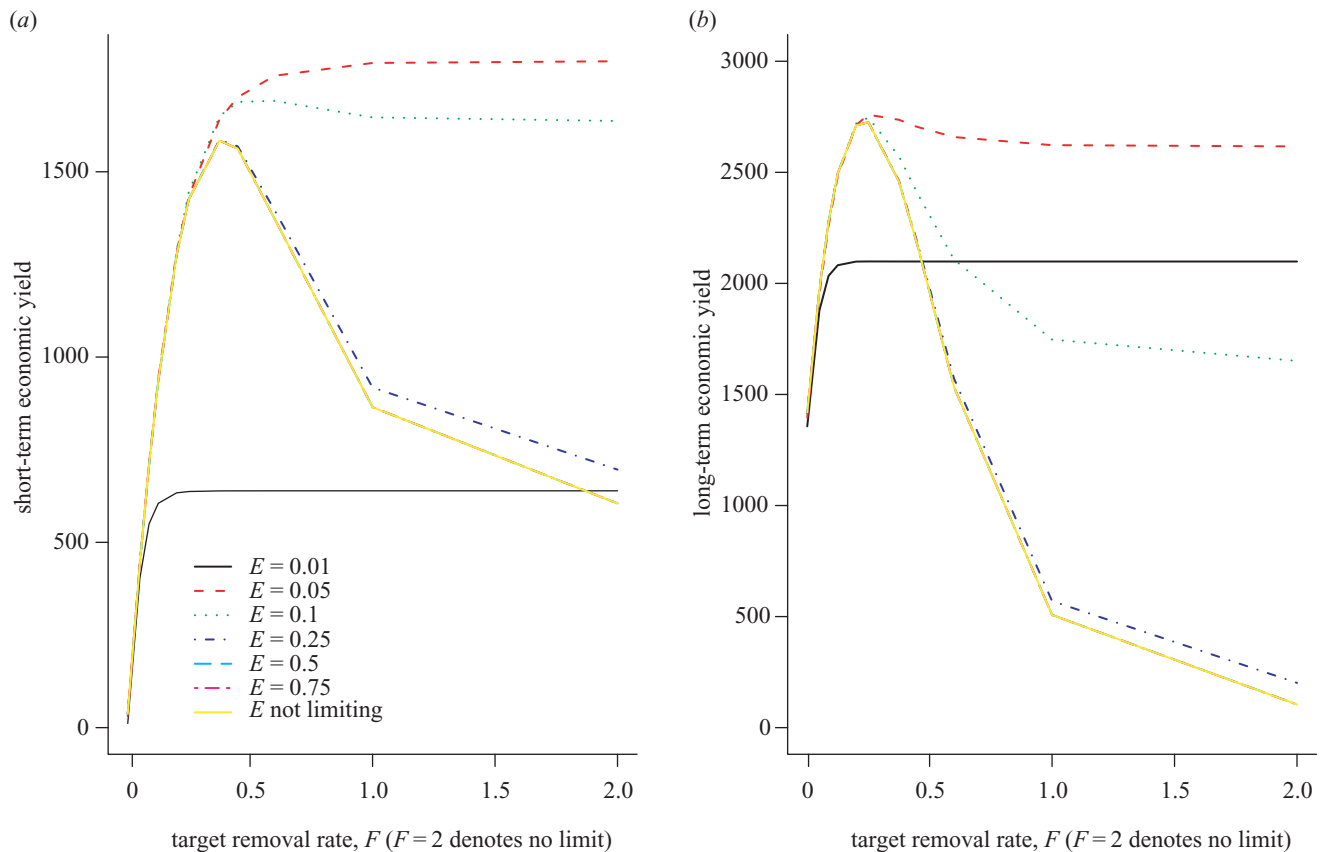


Figure 8. Effects of combinations of quota and effort controls on (a) short-term and (b) long-term profits. Each curve represents one effort level.

monitoring and enforcement of an MPA (position and activity of vessels) may be very different from that for quotas (landings and discards) and this difference may buffer against control errors.

Overall, our results show the benefits of combining control measures in protecting long-term economic yields by reducing the risk of stock collapse. Using substantial MPAs along with quota controls appears to have clear benefits for conservation and sustainability of fishery yields. In many cases internationally, more than one type of control measure is used in a single fishery management plan. It is important to note, however, that the benefits of multiple control measures will only be seen if each of the measure provides substantial restrictions on fishing. Simply having a closed area along with a quota will not help if neither results in a substantial check on fishing pressure.

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GLOSSARY

MPA: marine-protected area

MSY: maximum sustainable yield

TAC: total available catch