Closure strategies as a tool for fisheries management in metapopulations subjected to catastrophic events

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Abstract  Spatial management measures in the form of no-take areas used in fisheries management can provide a buffer against catastrophic events. Dynamic area closures, like rotational closures, have also been used as a management tool particularly for sessile organisms. In this study, bioeconomic models are developed to investigate dynamic closure strategies for use as a management tool in the harvest of a metapopulation consisting of two local sub-populations. The models provide an optimal strategy that maximises the sum of discounted net returns with a fixed harvest level [i.e. total allowable catch (TAC)] by opening and closing the sub-populations of a metapopulation, subject to random negative catastrophic effects. Results showed the optimal policy for opening and closing a single exploited population depends on the degree and pattern of migration between it and other sub-populations. When the harvest or TAC can be applied to either sub-population, the optimal closure strategy depends on the abundance of both populations, crucially, even if they are biologically independent. The results provide insights into the management of stochastically fluctuating populations including more mobile species that are frequently not subject to no-take controls.

KEYWORDS: bioeconomic model, management strategy, marine protected areas, marine reserves, rotational closures, total allowable catch.

Introduction

There is widespread recognition that spatial management measures in the form of no-take areas are a valuable tool for managing fisheries resources (Hilborn et al. 2004). Less apparent, however, is that spatial management measures convey benefits to fisheries beyond the boundaries of closed areas (Little et al. 2007) by providing either a source of emigrating fish, or dispersive larvae to the surrounding harvested areas.
While the yield benefits of marine reserves are still debated, the economic benefits from closing areas to fishing are becoming increasingly apparent (Pezzy et al. 2000). Both Sanchirico and Wilen (2001) and Grafton et al. (2005) showed how fisheries might benefit both economically and ecologically from marine reserves.

Spatial management measures, such as no-take marine reserves, require that the resource and its exploitation be considered in a spatially structured manner. Many populations of fish are spatially structured and consist of various sub-populations which combine to form a metapopulation (Levins 1969; Sale et al. 2006). Several authors have examined the exploitation of metapopulations (Man et al. 1995; Sanchirico & Wilen 1999). In particular, Sanchirico (2004) modelled an exploited metapopulation with marine reserves, showing the trade-offs and potential conditions where marine reserves could benefit a fishery both ecologically and economically. Tuck and Possingham (1994) calculated optimal harvest strategies for local sub-populations using a deterministic metapopulation model with larval exchange and subsequently (Tuck & Possingham 2000) determined optimal harvest strategies in a metapopulation when one of the sub-populations was closed to fishing.

Many bioeconomic models of marine reserves often examine harvest strategies through output controls like a total allowable catch (TAC) conditioned on a set amount of area closures (e.g. Grafton et al. 2005). In some fisheries, like those for sessile organisms, the use of more elaborate spatial management measures, like rotational closure strategies through opening and closing of areas, could also be used to increase economic return (Caddy 1993; Caddy & Seijo 1998; Hart 2003). Myers et al. (2000), for instance, concluded that rotational fishing has the potential to increase catches from stocks where incidental or indirect fishing mortality is an important factor, like scallops. Valderrama and Anderson (2007) found that closure strategies for scallops could also generate higher economic returns. Given that area closures are increasingly used to buffer or ameliorate periodic natural and human-induced catastrophes (Turner et al. 1999; Allison et al. 2003), closing an area to fishing at an appropriate time can potentially improve both the state of a stock and the economic returns from harvesting.

Rules or management arrangements for the opening and closing of fishing grounds may be specified by a fixed time period, or be adaptive and conditioned on other factors, such as the estimated number of animals in each area. Adaptive management strategies with a stochastically fluctuating resource are ideally suited to dynamic programming (Costello & Polasky 2008). In this study, such an approach was used to derive management strategies from bioeconomic models of a harvested metapopulation. The solutions determine the optimal strategy for opening and closing sub-populations that maximises the sum of the discounted net returns where the metapopulation is subject to a fixed harvest or TAC.

The analysis includes two different bioeconomic models. The first gives a decision rule for opening and closing an exploitable sub-population when one sub-population is permanently closed to fishing, while the second model gives a decision rule for opening and closing both sub-populations to fishing.

**Methods**

The first model imposes a fixed harvest on a single sub-population where the TAC is either taken (open) or not (closed). The effects on the optimal closure strategy of different levels of stochastic catastrophes and migration between the elements of the metapopulation are explored. The second model considers the case where a TAC is combined between two sub-populations so that the harvest can be taken from either one or the other sub-population, or split evenly between them. The control rule derived from the second model is the opening and closing combinations of the two sub-populations so as to maximise discounted net returns from fishing.

**Bioeconomic model with local TAC**

A metapopulation model, similar to Tuck and Possingham (2000), was specified with two sub-populations, one exploitable (sub-population 1) while the other (sub-population 2) was closed to fishing. Exploitation of the harvested sub-population, however, was set at a fixed level or TAC. Mixing or migration in the model was not restricted to larvae but applied to the whole population. Allowance was made for episodic catastrophes in the form of stochastic shocks to each of the sub-populations.

The optimisation problem was to maximise the sum of discounted net returns by opening and closing sub-population 1, with the reward per time step specified as:

\[
\Pi(t) = \left[ h^b_1 - \frac{c h_1}{X_1(t)} \right] (1 - s_1) 
\]

subject to the constraints of population dynamics given by.
\[
X_1(t+1) = \ddot{X}_1(t) + \dot{X}_1(t)r_1 \left[ 1 - \frac{\dot{X}_1(t)}{(\Phi_{1,1} + \Phi_{2,1})K_1} \right] - \dot{X}_1(t)\omega_1 - h_1(1 - s_1)
\]

\[
X_2(t+1) = \ddot{X}_2(t) + \dot{X}_2(t)r_2 \left[ 1 - \frac{\dot{X}_2(t)}{(\Phi_{1,2} + \Phi_{2,2})K_2} \right] - \dot{X}_2(t)\omega_2,
\]

where \(X_i(t)\) is the state variable representing the size of population \(i\) at time \(t\), \(h_1\) the TAC taken from population 1, \(s_1\) the control variable for population 1 (0: open, 1: closed), \(b\) a factor influencing the curvature of return per unit harvest and \(c\) a factor reflecting the cost per unit of harvest, at carrying capacity, \(K_i\), and the intrinsic rate of growth of population \(i\), \(K_i\) the carrying capacity of population \(i\) and \(\omega_i\) a random catastrophic event occurring to population \(i\) at time \(t\), which occurs as a Bernoulli trial with magnitude \(b_i\) and probability \(P_i\).

When the population is opened to fishing, the reward function consists of revenue, which increases with harvest, less costs, which increase with harvest, and decrease with the size of local sub-population. The biological populations are assumed to form a metapopulation, with sub-population mixing captured in each time period and governed by \(\Phi_{i,j}\). Population growth is density-dependent, with sub-populations subject to an independent catastrophic event, and there is no cost in closing and opening a sub-population. When the movement between populations is symmetrical (i.e. \(\Phi_{i,j} + \Phi_{j,i} = 1, i \neq j\)), \(r_i\) the intrinsic rate of growth of population \(i\), and \(\omega_i\) a random catastrophic event occurring to population \(i\) at time \(t\), which occurs as a Bernoulli trial with magnitude \(b_i\) and probability \(P_i\). The maximum sustainable yield (MSY) for each sub-population with no environmental stochasticity is:

\[
MSY_1 = \frac{1}{4}K_1r_1
\]

\[
MSY_2 = \frac{1}{4}K_2r_2.
\]

The sub-population sizes at the respective MSY levels, defined by \(B_{MSY}\), are:

\[
B_{MSY,1} = \frac{1}{2}K_1, B_{MSY,2} = \frac{1}{2}K_2.
\]

The default parameter values are provided in Table 1. The parameters for the reward function are based on the intrinsic rate of growth of population \(i\), \(K_i\) the carrying capacity of population \(i\) and \(\omega_i\) a random catastrophic event occurring to population \(i\) at time \(t\), which occurs as a Bernoulli trial with magnitude \(b_i\) and probability \(P_i\).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(b)</td>
<td>0.7</td>
</tr>
<tr>
<td>(c)</td>
<td>1.0</td>
</tr>
<tr>
<td>(r_i)</td>
<td>0.4 (for (i = 1,2))</td>
</tr>
<tr>
<td>(K_i)</td>
<td>1.0 (for (i = 1,2))</td>
</tr>
<tr>
<td>(b_i)</td>
<td>0.3 (for (i = 1,2))</td>
</tr>
<tr>
<td>(P_i)</td>
<td>0.3 (for (i = 1,2))</td>
</tr>
<tr>
<td>(\delta)</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Grafton et al. (2005), while the biological parameters were set to generate an MSY equal to 0.10, and a corresponding \(B_{MSY}\) of 0.5 for each sub-population. These parameters give a value of 0.061 for maximum economic yield (MEY) and a corresponding value of 0.81 for \(B_{MEY}\). As is the case in many fisheries, the TAC in this model was not set optimally to maximise the sum of the discounted net returns from harvesting. The benchmark TAC, \(h_1\) was set at a constant level less than \(MSY_1\), at 0.07 and more than \(MEY_1\), but the sensitivity of the results was also tested to different levels of harvest and catastrophic magnitude.

Sub-population 1 can either be opened or closed if the population falls below a threshold brought on by a catastrophic event while sub-population 2 is permanently closed. The optimal closure policy for sub-population 1 was calculated under different degrees of mixing between the two sub-populations. These conditions included the following cases: populations are independent, i.e.

\[
\Phi = \begin{bmatrix} 1.0 & 0 \\ 0 & 1.0 \end{bmatrix};
\]

populations are fully mixed

\[
\Phi = \begin{bmatrix} 0.5 & 0.5 \\ 0.5 & 0.5 \end{bmatrix};
\]

sub-population 1 is a biological source for the metapopulation

\[
\Phi = \begin{bmatrix} 0.9 & 0.1 \\ 0 & 1.0 \end{bmatrix};
\]

and sub-population 1 is a biological sink for the metapopulation

\[
\Phi = \begin{bmatrix} 1.0 & 0 \\ 0.1 & 0.9 \end{bmatrix};
\]

\[
\Phi = \begin{bmatrix} 1.0 & 0 \\ 0.5 & 0.5 \end{bmatrix};
\]
where element $\Phi_{ij}$ represents the proportion of population $i$ moving to population $j$.

**Bioeconomic model with combined TAC**

The case was also examined where a global TAC was divided between the sub-populations when they are both open to fishing. In this modification, the per period reward function is specified as:

$$\Pi = \sum_{i=1}^{2} \left[ h_i (1-s_i)(1-s_i+s_j) \right]^{b}$$

and the biological growth conditions are specified as:

$$X_1(t+1) = \frac{\tilde{X}_1(t)}{(\Phi_{11} + \Phi_{12})K_1} \left[ 1 - \tilde{X}_1(t) (1 - s_1) \right]$$

$$X_2(t+1) = \frac{\tilde{X}_2(t)}{(\Phi_{21} + \Phi_{22})K_2} \left[ 1 - \tilde{X}_2(t) (1 - s_2) \right]$$

The effects of the control variables $(s_1, s_2)$ on the reward and biological functions are that the harvest taken from population 1, when it is open ($s_1 = 0$), is $h_1$ (0.05) when population 2 is also open ($s_2 = 0$), and $2h_1$ (0.1) when population 2 is closed ($s_2 = 1$). The values for $h_1$ and $h_2$ were set to 0.05 so that when one sub-population is closed, the TAC of the other sub-population does not exceed MSY, $2h_1 = 0.1$. Thus, the TAC can be moved between sub-populations depending on the controlled state (open or closed) of the other sub-population.

For each of these two related problems, the Bellman equation for the infinite horizon dynamic optimisation problem, which represents the payoff from the choices of the control variables $(s_1, s_2)$ and the value of the remaining decisions that result from those choices, is given by,

$$V(X_1(t),X_2(t)) = \max_{s_i=0.1} \left\{ \Pi + \delta E[V(X_1(t+1),X_2(t+1))] \right\}.$$ 

where $s_i$ are the control variables for the problems (i.e. $i = 1$ for the local TAC problem, and $i = 1, 2$ for the combined TAC problem) and $\delta$ the economic discount factor.

Both models (local TAC and combined TAC) were solved under a range of different conditions using the numerical collocation technique (Miranda & Fackler 2002).

**Results**

**Bioeconomic model with local TAC**

The solution of the local TAC optimisation problem defined by equations (1–3), in which sub-population 2 is permanently closed while sub-population 1 is exploited at a set harvest level generated the optimal strategy or policy for opening and closing for the harvested sub-population. The closure threshold that maximised the net discounted return decreased with harvest, where sub-populations are independent $\Phi = \begin{bmatrix} 1.0 & 0.0 \\ 0.0 & 1.0 \end{bmatrix}$.

![Figure 1. Threshold population levels for closing sub-population 1 that optimise net discounted returns, as a function of different values of harvest, where sub-populations are independent $\Phi = \begin{bmatrix} 1.0 & 0.0 \\ 0.0 & 1.0 \end{bmatrix}$.](image)
therefore relatively small, and so future benefits from high stock size that reduces per unit harvesting costs and raises net returns also declined making it less worthwhile to close the fishery.

Figure 3 shows the optimal closure strategies as a function of both sub-populations and the long-term state of the sub-populations when they are not harvested, but subject only to catastrophic events (circle). For the case when the sub-populations are independent, the optimal closure strategy for harvesting sub-population 1 was independent of the state of population 2 (Fig. 3a) and corresponded to the closure threshold in Fig. 2a under the conditions $\beta = 0.3, P(\beta) = 0.3$. As the degree of mixing increases between the populations, however, the closure threshold for population 1 becomes dependent on the state of not only sub-population 1, but also sub-population 2 (Fig. 3a) where a larger exploitable population due to mixing resulted in a threshold for closing sub-population 1 that decreased overall.

At low levels of sub-population 2 and high levels of mixing, the threshold for harvesting sub-population 1 declined (Fig. 3a). This result is also counter-intuitive but occurred because compensation or surplus production in sub-population 2 at lower stock levels was reduced, generating a net migration to sub-population 2 from the harvested sub-population 1. Consequently, the size of sub-population 1 was reduced because of these transfers, and so the threshold for harvesting was correspondingly reduced to help offset this effect.

When sub-population 1 was a source, the harvest threshold was lower than if it were independent (Fig. 3b) to account for a reduced stock size as a result of emigration. When sub-population 1 was a sink to the metapopulation, the closure threshold was also reduced, but this depended on the state of the unexploited population (Fig. 3b). When the level of sub-population 2 approached zero it cannot provide sufficient fish to offset higher catches in sub-population 1 and the resulting closure was similar to the case where the two sub-populations were independent of each other. In contrast, as the state of sub-population 2 approached its carrying capacity, it provided greater input or spillover to sub-population 1 that allowed the threshold level (as proportion of the exploited population) for closure to decrease.

**Bioeconomic model with combined TAC**

A wider set of results was obtained if the fixed TAC was combined between the sub-populations. There are four general combinations of opening and closure of the two local populations. For example, sub-population 1 could be closed or open depending on whether sub-population 2 is closed, harvested at 0.05 or at 0.1.
Figure 4 shows the control rules under different levels of mixing between the sub-populations. The mixing in these cases is symmetrical and does not represent a source–sink relationship. Consequently, the control rules for closure for both sub-populations are also symmetrical. For reference, Fig. 4 also shows the long-term population states when they are harvested under the given control rules (triangle) and when they are not harvested, but subject only to catastrophic events (circle).

The optimal control rule for this model is that if the current state of sub-populations 1 and 2 are 0.5 and 0.3 respectively, then the optimal policy is to close both populations to fishing (Fig. 4, point a). However, if the state of sub-population 1 state is higher, at above about 0.7, then it should be opened and thus harvested at 0.1, while sub-population 2 is closed (Fig. 4, point b). If however, the state of sub-population 2 is between about 0.5 and 0.75 while sub-population 1 remains at 0.5, then there is enough of the resource in both populations.
populations for the TAC to be split between them both (Fig. 4, point c). If, however, sub-population 2 were even higher, above 0.75, but sub-population 1 were at 0.5, then it is preferable, if the sub-populations are biologically independent, to close population 1 and to harvest population 2 at the higher level, 0.1 (Fig. 4, point d).

The reason for the pattern in the closure control rule is the inverse relationship between cost of harvest and biomass. Namely, it is more profitable to stop exploiting a smaller population that has a higher cost of exploitation, and to harvest from the more abundant population where the harvest can be taken at lower cost.

The optimal control of sub-population 1 was affected the most when sub-population 2 was large. At levels below 0.4, sub-population 2 had little effect on the optimal control of sub-population 1 (Fig. 4). At levels above 0.4, sub-population 2 had a strong influence on whether sub-population 1 was harvested. In particular, when sub-population 2 was close to its carrying capacity, the closure threshold for sub-population 1 was relatively high, as there is a greater payoff from closing sub-population 1 and harvesting only sub-population 2. However, as sub-population 2 decreased in size, the closure threshold for closing sub-population 1 also declined (Fig. 4). This continued until the lowest closure threshold when the size of sub-population 2 was about 0.6 and sub-population 1 was about 0.4. At lower levels of sub-population 2, the alternative management arrangement to both sub-populations being open was both being closed. As the state of sub-population 2 decreased, the closure threshold of sub-population 1 compensated by increasing, to a point; at a level below about 0.4, after which sub-population 2 had little effect on the management status of sub-population 1.

Figure 4. Optimal closure thresholds of sub-populations in a metapopulation as a function of the state of each sub-population relative to its carrying capacity $K$, under different conditions of sub-population mixing, and when the harvest could be applied to one both or neither of the sub-populations. The expected population levels of harvested populations were generated under biological conditions $\Phi = \begin{bmatrix} 1.0 & 0.0 \\ 0.0 & 1.0 \end{bmatrix}$ and the corresponding optimal harvest policy. For letters (a,b,c,d), see text.
As in the case when sub-population 2 was permanently closed, the optimal management strategies were affected by migration between the sub-populations. In particular, for the control strategy for sub-population 1, at relatively high biomass levels of sub-population 2, such as those $>0.6$, increased migration consistently led to lower closure thresholds (Fig. 4). At lower sub-population 2 levels, however, such as those below about 0.4, the effect was less clear. Nevertheless, it appears the closure strategy for sub-population 1 becomes increasingly dependent on the level of sub-population 2 the greater the two populations mix.

Discussion

Few authors have derived optimal strategies for opening and closing different areas. An exception is Tuck and Possingham (1994) who implicitly derived closure policies for a spatially structured metapopulation. In the current modelling, the TAC was fixed and then harvesting was allowed to occur on either or both sub-populations with an optimally derived closure rule defined by the relative biomass. This approach, which allows for mixing and migration and interdependence, can be applied to both sessile (Caddy 1993) and highly mobile species and not just species with only a mobile larval stage (Tuck & Possingham 2000).

A key result was that the optimal closure strategy depended on the states of sub-populations even when the populations do not interact biologically. This result arises from the bioeconomics whereby smaller populations result in higher per unit harvesting costs and reinforces previous findings that costs can play an important part in the optimal exploitation of spatially structured populations (Sanchirico & Wilen 1999; White et al. 2008). This underscores the importance of understanding fleet behaviour as optimal closure policies depend on consolidated fleet decisions and movements (Hilborn & Ledbetter 1979; Little et al. 2004).

Many modelling studies of fisheries showed the importance of area closures in mitigating the effect of catastrophic events, and that as the magnitude and occurrence of catastrophic events increased, reserve size should increase to optimise fishery returns (Doyen & Béné 2003; Grafton et al. 2006; Doyen et al. 2007). In contrast, the current study showed that as the magnitude and occurrence of catastrophic events increased, the closure threshold of a single exploited population can decrease and become more likely to be exploited. This result is also obtained if the exploited population is a population source for the metapopulation such that when the exploited population decreases in size it becomes more likely to be exploited. These important and counterintuitive results occur because the expected biomass of the exploited population decreases the more likely is the incidence and the more severe is a negative shock, and also when emigration from the exploited and source population is the greatest. The degree to which the closure threshold was reduced as a result of increased occurrence and severity of catastrophes (Fig. 2a) however, was much less relative to the reduction in expected stock size (Fig. 2b), and so should be considered when contrasting the results of Grafton et al. (2006). Nevertheless, this set of results emphasise the importance of uncertainty, in both the assumed biological process as well as the representative model (Francis & Shotton 1997; Yamazaki et al. 2009), on the development of management strategies and their expected performance.

In general, rotational closure strategies used as a fisheries management tool are often set for fixed time periods. For example, Williams et al. (2006) looked at 20 years of data from a 2.5-km-long coastal coral reef area and found that fish biomass increased during 1- and 2-year closure periods, but these closure periods were still not enough to compensate for a quick decline that occurred when fishing was resumed. Before a more adaptive framework was developed to include scientific advice, the sea cucumber fishery in British Columbia was previously managed on a fixed 3-year rotation (Perry et al. 1999). Making closure policies adaptive (e.g. Hart 2003), however, requires knowledge on the state of the resource, and the stochastic fluctuations in it. This demands that managers have reliable estimates of stock size and represents a formidable obstacle in implementing optimal closure control policies in practice. Despite this caveat, and general criticisms of applying optimal control solutions to actual natural resource management (Holling & Meffe 1996; Béné et al. 2001; Anderies et al. 2007), the control strategies that emerge from the current modelling can be used to design management strategies. A management strategy evaluation (MSE: Sainsbury et al. 2000) approach could, for example, evaluate the implications of applying a control closure policy to fisheries where the dynamics of the underlying resource, and its exploitation, are more complicated than that under which the policy was derived. The MSE approach also has the benefit of being able to evaluate the effect of inaccurate resource estimates, i.e. assessment uncertainty (cf. Francis & Shotton 1997) on outcomes.

In summary, optimal closure strategies for closing and opening areas to fishing are a potentially valuable management tool for fisheries management. Although
such strategies require knowledge of the spatial structure and population dynamics, they are comparatively easy to enforce (Myers et al. 2000) and may also provide insurance against uncertain events (Grafton et al. 2006).

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References


