Exogenous shocks and marine reserves

Work in progress

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Abstract

The impact on the value of a fishery from exogenous shocks is investigated. A part of the habitat is protected by a marine reserve, and the remaining fishery is managed by optimal, total allowable catch quotas. Shocks of different, spatial nature is investigated. The results suggest that reserves are of minor interest as a management tool when shocks affect the stock uniformly. Reserves may substantially enhance the value of the fishery when shocks are spatially non-uniformly distributed.

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Introduction

Marine reserves has received considerable attention from both biologists and economists, as well as other groups of scientists, over a period extending more than 15 years back. Grafton et al. (2005) provides an excellent and thorough review of the most important contributions to the economic literature. Studies of uncertainty and pertaining bioeconomic perspectives are limited, however (Grafton et al. 2005). With the main focus on the biology, Lauck et al. (1998) finds that the reserve size should increase with the level of uncertainty about the stock size. Sladek Nowlis and Roberts (1999) and Conrad (1999) shows that reserves reduce the variation in the stock level when the environment fluctuates. Further, Hannesson (2002) studies a stochastic model of a fishery and concludes that reserves may reduce the variation in catch. These are interesting results, particularly in light of the growing concern related to global warming.

This paper aims to extend the analysis in Kvamsdal and Sandal (2008), where the economic and biological impacts of a marine reserve is investigated. A marine reserve is geographically defined area covering parts of a fish stock's habitat which is closed to fishing (Hannesson 1998). In a deterministic setting Kvamsdal and Sandal (2008) numerically calculates optimal harvesting policies for different parameter configurations and initial conditions. In this paper I apply the optimal policies and study the expected economic effect of exogenous shocks to the stock level. Different probability distributions for the exogenous shocks are considered. To my knowledge, very little attention has previously been brought to the question of distributions. However, the distribution issue arises naturally along with the idea of shocks to a capital stock. Further, I study the effects from both totally exogenous shocks and shocks explained by the harvesting activity, *i.e.*, no shock occur in the area protected from fishing. The main finding is that reserves have little or no value when shocks occur in the entire habitat. This holds also when the probability distribution of the shocks is skewed towards negative shocks. When shocks are limited to the exploited area, reserves are found to increase the value of the fishery considerably. Not surprisingly, the effect from a reserve increases as the variance in the probability distribution increases.

A key feature of the current approach is the combination of reserves with total catch quotas to manage the fishery. It has been demonstrated that reserves as the only regulation effort cannot achieve much in economic terms and perhaps not even when it comes to conservation of the stock (Hannesson 2002). There are evidence that reserves may in some aspects be successful in an uncertain world (Conrad 1999, Hannesson 2002, Lauck et al. 1998, Sladek Nowlis and Roberts 1999). Notwithstanding, there is a wide consensus that reserves should be combined with complementary regulations (Grafton et al. 2005, Sanchirico 2000, *i.a.*).

The Model

The basic model is the same as that in Kvamsdal and Sandal (2008), and goes back to Hannesson (1998). In principal, the model is deterministic. I will return to how uncertainty is introduced. A continuous time surplus production model is supposed to describe the bionomical relations. A simple profit function is maximized with respect to the biological dynamic equations. The key features in the model are logistic growth functions, linear diffusion of biomass between the reserve and the rest of the habitat, a Schaefer production technology, and a downward sloping demand for fish. I will attend to each of them in turn

The habitat of the fish stock in question is divided into two subareas. The biomass in each area grow according to the logistic growth law. That is, the growth in area i is given by

$$f(x_i, K_i) = rx_i \left(1 - \frac{x_i}{K_i}\right)$$

where x_i is the biomass, r is the intrinsic growth rate, and K_i is the carrying capacity. Let area 1 denote the area left open to fishing activity, and area 2 the protected habitat. Further, let s measure the fraction of habitat under protection. Thus, the carrying capacity in the protected and remaining, unprotected area is sK and $(1-s)K$, respectively. K is the total carrying capacity in the entire habitat. Both r and K are normalized to 1 without loss of generality.[1]

The two substocks, as I now call them, exist in each their subarea and interact through migration. Migration is modeled as a diffusion process. I want to keep the model as simple as possible, hence, migration depends linearly on

[1] It is worth noting that this formulation of the growth functions imply a different total growth than what would arise if the biomass was aggregated over the entire area, unless of course when the *density of fish* is equal in both areas. Then the growth models are equivalent. There is a short discussion of this problem in Kvamsdal and Sandal (2008).

the difference in density of fish in the two areas;

$$\phi\left(\frac{x_2}{s} - \frac{x_1}{(1-s)}\right)$$

where ϕ is the rate of migration.

The change in biomass in each area may now be described by the dynamic equations

$$\left.\begin{array}{rcl}\dot{x_1} & = & f(x_1,(1-s)) + \phi\left(\frac{x_2}{s} - \frac{x_1}{1-s}\right) - h \\ \dot{x_2} & = & f(x_2,s) - \phi\left(\frac{x_2}{s} - \frac{x_1}{1-s}\right)\end{array}\right\} \quad (1)$$

The dot-notation is a short-hand notation for the time derivatives. h is harvest. Notably, migration cancels out in the two areas. That is; nothing is lost neither gained in the diffusion process. Naturally for a diffusion process, net migration points out of the area with the higher density. All fishing activity is located in area 1.

The success of fishing effort is governed by the Schaefer function. That is, $h = qEx_1$, q is the catchability coefficient, E is the effort applied by the fishing fleet, and x_1 is the biomass in the area open to fishing. Again, this particular functional form is chosen due to simplicity. Note that any dynamic in the fleet, such as problems with overcapacity, is beyond my scope here and is ignored. Notwithstanding, such issues are important to the success of fisheries management and pose further possible extensions of this work. There is a cost c related to each unit of effort. Thus, for a given catch h, the total cost is

$$cE = c\frac{h}{qx_1}$$

That is, depending on the ratio of catch to biomass in the unprotected area. This is known as a stock effect on costs. The stock effect can be comprehended as an economic protection from extinction; costs blow up when the biomass approaches zero. Of course, this depends on the uniform dispersion of biomass in each area, something which underlies the logistic growth function.

The last key feature of the model is the downward sloping demand for fish. This is a feature which may seem unnecessary in terms of simplicity and generality. However, as I am investigating an *optimal* management scheme based on TACs, it is convenient that the profit function, which I will formulate shortly, is nonlinear in the harvest term, h. A downward sloping demand is one way to do that. Normalizing, the unit price of fish is given by $1 - dh$, where $-d$ is the slope of the inverse demand function. The profit function may now be written as

$$\pi(x_1, h) = (1 - dh - \frac{x_0}{x_1})h$$

where x_0 is $\frac{c}{q}$, adjusted to the normalization of the price of fish and the carrying capacity of area 2.[2] x_0 may be interpreted as the *open-access* density of fish; the bionomic equilibrium level (Clark 1990).[3] It is worth noting that the profit function only depends on the stock level area 1 directly and indirectly on the stock level in area 2 through the biomass interaction between the areas.

As mentioned, the fishery is managed through TACs by a sole owner (or single agent) with an infinite time horizon. The problem of the sole owner is described as

$$\max_{h \geq 0} \int_0^\infty \mathrm{e}^{-\delta t} \pi(x_1, h) \, \mathrm{d}t \tag{2}$$

which is subject to the dynamic equations in (1), and initial conditions

$$x(0) = x^0 = (x_1^0, x_2^0) \tag{3}$$

where t is time, δ is the rate of discount, and x_i^0 is the stock level in area i at time $t = 0$.

Let m_i be the current value multipliers (or shadow values) of x_i, and let $\mathscr{H}(x_i, m_i, h)$ be the current value Hamiltonian associated with the problem at hand. The Hamiltonian is given by

$$\begin{aligned}
\mathscr{H}(x_1, x_2, m_1, m_2, h) \quad = \quad & \pi(x_1, h) \\
& + m_1 \cdot \left(f(x_1, (1-s)) + \phi \left(\frac{x_2}{s} - \frac{x_1}{1-s} \right) - h \right) \\
& + m_2 \cdot \left(f(x_2, s) - \phi \left(\frac{x_2}{s} - \frac{x_1}{1-s} \right) \right)
\end{aligned}$$

[2] That is, the unit price of fish may be written $p(1 - dh)$. Then, $x_0 = \frac{c}{pq(1-s)}$. I have normalized the price; $p = 1$.

[3] Downward sloping demand is only one of several possible interpretations of the profit function. It is, however, an interpretation which is straightforward and readily intuitive from the expression. The 'demand term' may represent any cost in a fishery depending solely on the size of the catch, be it related to fleet size, wage structure, transportation, etc., and the reader is invited to give it the interpretation he sees fit.

Then, the first order conditions of this problem is given by

$$\begin{aligned}
\dot{x_1} &= f(x_1,(1-s)) + \phi\left(\frac{x_2}{s} - \frac{x_1}{1-s}\right) - h \\
\dot{x_2} &= f(x_2,s) - \phi\left(\frac{x_2}{s} - \frac{x_1}{1-s}\right) \\
\dot{m_1} &= \delta m_1 - \tfrac{x_0}{x_1^2} h - m_1 \cdot \left(1 - 2x_1 - \tfrac{\phi}{1-s}\right) - m_2 \tfrac{\phi}{s} \\
\dot{m_2} &= \delta m_2 - m_1 \tfrac{\phi}{1-s} - m_2 \cdot \left(1 - 2x_2 - \tfrac{\phi}{s}\right) \\
h &= \arg\max_h (\mathscr{H})
\end{aligned}$$

Despite efforts to keep things simple, analytical solutions of this problem are elusive, if not beyond recognition, and I resort to a numerical study of the properties of the solutions. A dynamic programming scheme provides optimal harvest rules in feedback form; *i.e.*, depending on initial stock levels. The numerical scheme also provides the value of the fishery, that is, the value of the expression in (2), which also is depending on initial conditions. These functions; the harvest rules and value functions, are calculated in Kvamsdal and Sandal (2008). Parameter values considered are found in Table 1. These parameters are kept fixed throughout the analysis. For more nitty-gritty details, discussions, and references related to the basic model and the numerical scheme, the reader is referred to Kvamsdal and Sandal (2008).

I proceed in the following way. The system is assumed to be in the optimal steady state $x^* = (x_1^*, x_2^*)$ at time zero. An initial shock of relative size ϵ then yields the initial condition

$$x^0 = x^* \cdot (1 + \epsilon) \tag{4}$$

The shock size is, in other words, measured as a fraction of the optimal steady state stock level. Alternatively, I consider shocks only in area 1; the area open to fishing. That is, $x^0 = (x_1^* \cdot (1+\epsilon), x_2^*)$. I will refer to these two types of shocks as uniform and non-uniform, respectively. The non-uniform shocks are motivated by the idea that an exploited stock is more fragile to fluctuations,

Parameter	Value	Explanation
δ	.05	Discount rate
x_0	.15	Open-access density
d	.0005	Demand parameter
ϕ	.2	Migration rate

Tab. 1: List of parameters.

e.g. of the environment. The shocks take values in the interval $(-0.9, 0.9)$ (that is, symmetric around zero), thus avoiding the adverse equilibrium $x = (0, 0)$ as initial condition. Shocks are distributed according to a beta probability distribution. Both symmetric and asymmetric distributions are considered. For a given size of the protected area (s), I take the expectation of the change in value.

Measures

Let $V(s, \epsilon)$ be the value of the fishery for a given size of the protected area, s, and shock, ϵ. Formally, $V(s, \epsilon)$ is given by the expression in (2), with (4) as the initial condition. The expected effect of an initial, single shock may then be described by the expression $\Delta_u(s) = \mathrm{E}_\epsilon[V(s, \epsilon)/V(s, 0) - 1]$ for any given size of the protected area. The subscript indicates what effect the measure captures; u stands for *uncertainty.* I am not only interested in the isolated effect of shocks, as given above. I am also interested in how the marine reserve performs under uncertainty. The deterministic effect, as I choose to call it, of the reserve is given by $\Delta_d(s) = \dfrac{V(s, 0)}{V(0, 0)} - 1$. (The expectancy operator is unnecessary.) This effect is studied comprehensively in Kvamsdal and Sandal (2008) (see, for example, equation (1) and Figure 1). The combined effect from the reserve and a single, initial shock is then

$$\Delta(s) = \mathrm{E}_\epsilon \left[\frac{V(s, \epsilon)}{V(0, 0)} - 1 \right]$$

One may, at least in a figuratively and non-literal way, imagine $\Delta(s)$ as the sum of $\Delta_u(s)$ and $\Delta_d(s)$.

Alternative to $\Delta_u(s)$ defined above is the measure defined by $\Delta_s(s) = \mathrm{E}_\epsilon \left[V(s, \epsilon)/V(0, \epsilon) - 1\right]$, which isolates the effect of the reserve upon a given uncertainty structure. (The subscript s reflects our notation for the area size.) This effect is called the reserve effect and I will discuss it later.

More interesting than single, initial shocks, are repeated shocks. To make things simple, I assume that shocks occurs in each time period, and that each shock has the same expected effect on the value of the fishery. That is, the accumulated, combined effect from shocks in each time period and a marine protected area of size s is given by

$$\widehat{\Delta(s)} = \int_0^\infty \mathrm{e}^{-\delta t} \Delta(s) \, \mathrm{d}t$$

This can be decomposed into different parts, in the same fashion as in the single shock case.

A few critical words on the model; It is a weakness that the optimal harvesting rules are derived from a deterministic model, and thus do not take uncertainty into account. In the case where only single, initial shocks are considered, the harvesting rules are indeed optimal. In the case of repeated shocks, the harvesting rules are suboptimal, however. Nonetheless, they are of *feedback* type, and shocks are thus taken into account when they are realized (observed). The probability of future shocks is not taken into account. By motivating the exogenous shocks as a realization of 'true uncertainty' (Lauck et al. 1998), which are difficult or impossible to discern, the given harvest rules may be seen as the most cost-efficient alternative for the managing agent. This does not mean that it is *impossible* to take such uncertainty into account. It is, however, hard to model and treat satisfactorily within the current framework. A more appropriate approach to investigate such uncertainty is maybe a viability framework; see Doyen and Béné (2003) for an application to marine reserves.

Another feature of the approach is that when finding the accumulated effect from repeated shocks, it is assumed that the system is in its steady state before each new shock. This is not necessarily true when shocks occur often (it always takes some time to rebuild the stock after negative shocks, depending on the growth rate and the size of the shock). The assumption is, however, a convenient simplification.[4]

Results

Before I present the main results, a quick look on the different probability density functions which are considered is due. These are presented in Figure 1. The shocks take values in the discrete set $\{-0.90, -0.85, -0.80 \dots 0.80, 0.85, 0.90\}$.[5] The density functions are beta distributions, which is specified by two parameters. Formulas and a short discussion of the beta distribution are found in the appendix. The current distributions correspond to the following set of parameters; $\{(1, 1), (2, 2), (5, 5), (2, 5)\}$. I will refer to these as the 'uniform', 'concave',

[4] I am aware that this is not an innocent assumption; at least, its innocence depends on a range of factors such as the time it takes for the system to return to the steady state, which again is related to the size of shocks. I am currently working on implementing a weaker assumption and a more comprehensive approach to the problem. A short discussion on alternative methods is found towards the end of the paper.

[5] That is, the probability density functions are actually step-functions; they are discrete. To enhance readability, however, the curves in Figure 1 are drawn smooth.

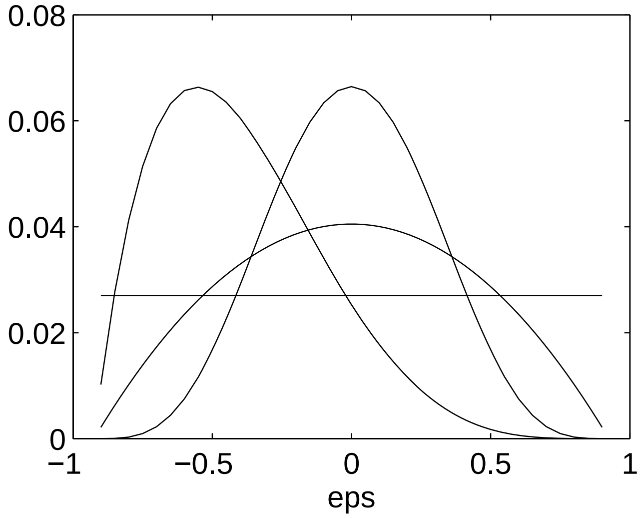


Fig. 1: Probability densities for the different shock sizes, with the parameter pairs $\{(1,1),(2,2),(5,5),(2,5)\}$. The different functions can be described and identified by the following tags, respectively; 'uniform', 'concave', 'bell-shaped', and 'skewed'.

'bell-shaped', and 'skewed' distributions, respectively.[6] The names are easily connected to the different curvatures of the distributions. The mean and variance of the different probability distributions are found in Table 2. The three first specifications have zero mean and are symmetric. The last specification, however, has a negative mean and is asymmetric. The motivation for looking at a distribution of shocks with negative means is, *e.g.*, shocks caused by overfishing or environmental catastrophes.

[6] I trust the reader not to confuse the 'uniform' probability distribution with the uniform type of shock.

Probability distribution	Parameters	Mean	Variance
uniform	(1,1)	.0	.15
concave	(2,2)	.0	.09
bell-shaped	(5,5)	.0	.04
skewed	(2,5)	-.38	.05

Tab. 2: Probability distributions.

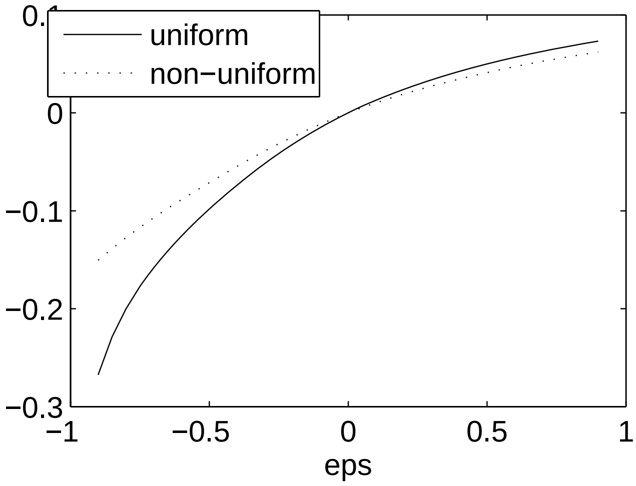


Fig. 2: Change in value due to shocks in the stock levels when the protected area is covering half the fishing grounds; $\dfrac{V(0.5,\epsilon)}{V(0.5,0)} - 1$. The effect from both uniform (solid) and non-uniform (dotted) shocks are calculated.

Single, initial shocks

Underlying the subsequent results is the change in value of the fishery from a single, initial shock to the steady state stock level. The effect obviously depends on the size of the protected area; the larger the reserve, the smaller the effect from a shock. Further, I consider two different types of shocks; uniform shocks, which affect the stock in the entire habitat in the same manner, and non-uniform shocks, which only affects the unprotected sub-stock. Note that the change from a single, initial shock of a given size is independent of the probability of the shock. How different shocks change the value when half the habitat is protected is recorded in Figure 2. Of course, a zero shock has no effect. Positive shocks have a positive effect; negative shocks have a negative effect. Further, the effect is smaller when the shock is non-uniform; a smaller part of the total biomass is affected. It is worth noting that negative shocks have larger impacts than positive ones of similar size. This relates directly to the concave growth functions and the concave harvest rule. Specifically, whenever the mean of the probability distribution of the shocks is nonpositive, the expected change in value is negative for all area sizes.

The next step is to take the expectation over the different shocks for each level of protection, that is, for each value of s, and get $\Delta_u(s)$. Figure 3(a) shows how this plays out for different probability distributions and uniform shocks. Not surprisingly, the 'uniform' distribution, which has the largest variance, yields the largest impact. All distributions considered in Figure 3(a) have mean zero, and the expected effect is negative for all s (as established in the previous paragraph). Further, note that a larger protected area reduces the effect.

Letting the shocks be spatially non-uniformly distributed reduces the expected effect from shocks. The reduction of the effect is increasing in s. This is demonstrated in Figure 3(b) for the 'concave' probability distribution.

A striking observation in Figure 3 (and subsequent figures) is the notorious lack of smoothness in the resulting curves. Of this, I can offer no other explanation than an unhappy marriage between a concave value function and a weighted expectation operator applied to concave curves as those in Figure 2.

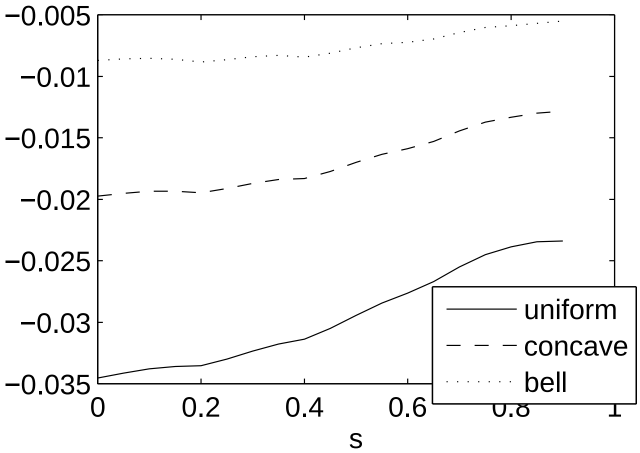
Thus far, I have, given the existence of a reserve, established that reserves partially offset the effect from exogenous shocks to the (steady state) stock level. However, the reserve itself induces a cost to the sole owner; *i.e.*, the deterministic cost $\Delta_d(s)$. It is possible to compare these effects in such a way as to decide on an optimal protected area size. Note that $\Delta_d(s)$ is independent of both the probability distribution of shocks, and the type of shocks. $\Delta_d(s)$, under the given parametrization, is displayed in Figure 4; again, see Kvamsdal and Sandal (2008) for a comprehensive discussion of the effect (where it is called the *premium* of the reserve). In the same figure, $\Delta(s)$ is drawn for uniform shocks with a 'concave' probability distribution. It is evident that $\Delta_u(s)$ and $\Delta_d(s)$ operates on different scales,[7] which is no surprise. The former measures the effect from a one-time event; a single shock to the stock level, whilst the latter measures the effect of having a marine reserve in place forever; in a sense, infinitely many events. $\Delta_d(s)$ is the dominating effect for all s, and the optimal choice would be to have no reserve.

Repeated shocks

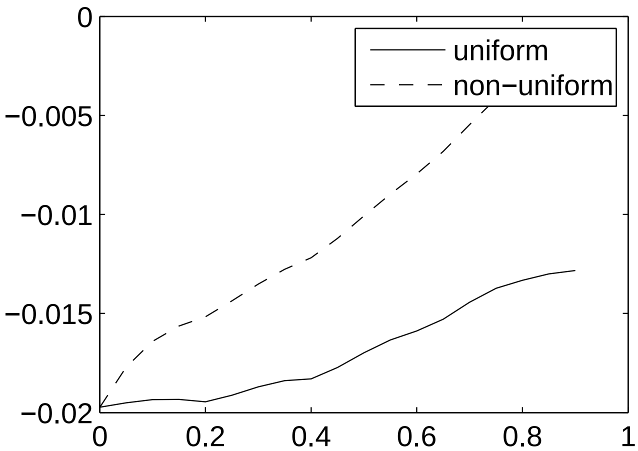
By letting shocks occur in every period, instead of just initially, the induced effect is the result from infinitely many events in much the same manner as in $\Delta_d(s)$. The uncertainty effect[8] is displayed in Figure 5(a) and (b) for uniform

[7] $\Delta_u(s)$ accounts for the difference between $\Delta(s)$ and $\Delta_d(s)$, see Figure 4.

[8] Here, I actually look at a 'normalized' effect $\widehat{\Delta'_u(s)} = \widehat{\Delta_u(s)} - \Delta_u(0)$, such that $\widehat{\Delta'_u(0)} = 0$. It follows that $\widehat{\Delta'_u(s)}$ takes on positive values, cf. $\Delta_u(s)$ in Figure 3, which takes on negative



(a)



(b)

Fig. 3: $\Delta_u(s)$: (a) Expected change in value of the fishery from single, uniform shocks, for different protected area sizes s, under different probability distributions. (b) Expected change in value from single, non-uniform shocks, for different protected area sizes s, under the 'concave' probability distribution.

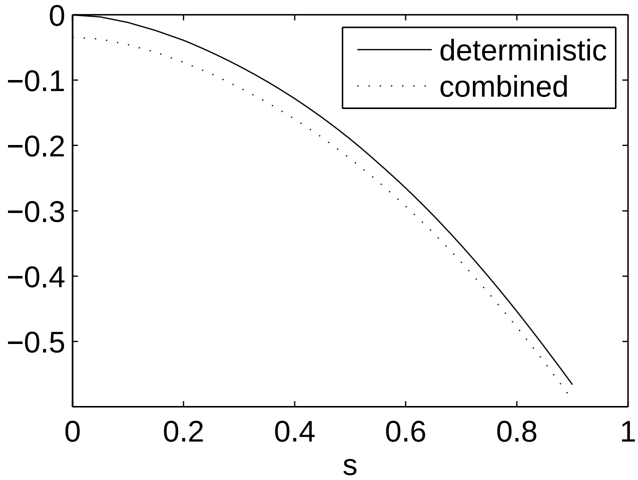


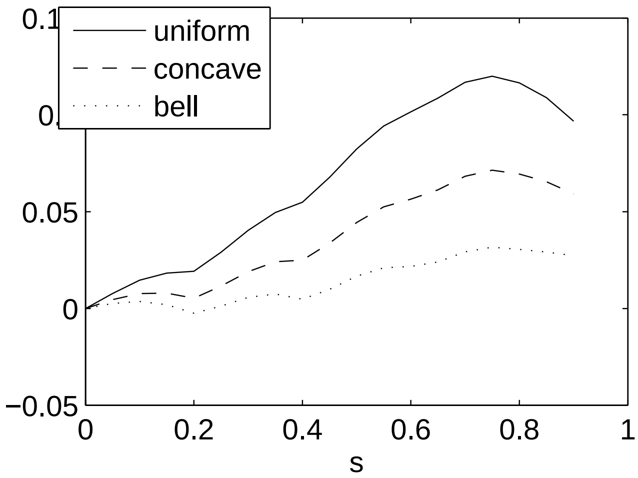
Fig. 4: Comparing the deterministic effect ($\Delta_d(s)$; solid) with the combined effect ($\Delta(s)$; dotted), under uniform shocks and the 'concave' probability distribution.

and non-uniform shocks, respectively, under different probability distributions. The 'uniform' probability distribution yields the largest effect under both types of shocks, and the non-uniform shocks induces larger effects than the uniform shocks. The effects seen in Figure 5 more than offset $\Delta_d(s)$ for some reserve sizes; thus, there is a positive, optimal reserve size in each case. The optimal reserve sizes for each scenario is given in Table 3. Moreover, it seems like the main effect from considering non-uniform shocks is an amplification of the corresponding effect under uniform shocks.

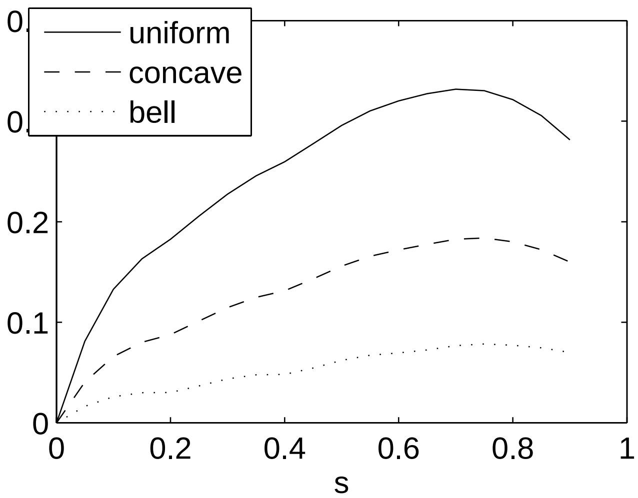
values.

Prob. distr.	s^*	V^*	Shock type
uniform	.05	.0047	unif.
concave	.05	.0015	unif.
bell-shaped	.0	.0	unif.
skewed	.05	.0042	unif.
uniform	.30	.1481	non-unif.
concave	.15	.0557	non-unif.
bell-shaped	.10	.0140	non-unif.
skewed	.25	.2245	non-unif.

Tab. 3: Optimal reserve sizes and corresponding change in value under repeated shocks.



(a)



(b)

Fig. 5: (a) $\widehat{\Delta'_u(s)}$; the uncertainty effect from repeated, uniform shocks, for different protected area sizes s, and probability distributions. (b) The uncertainty effect from repeated, non-uniform shocks, for different protected area sizes s, and probability distributions.

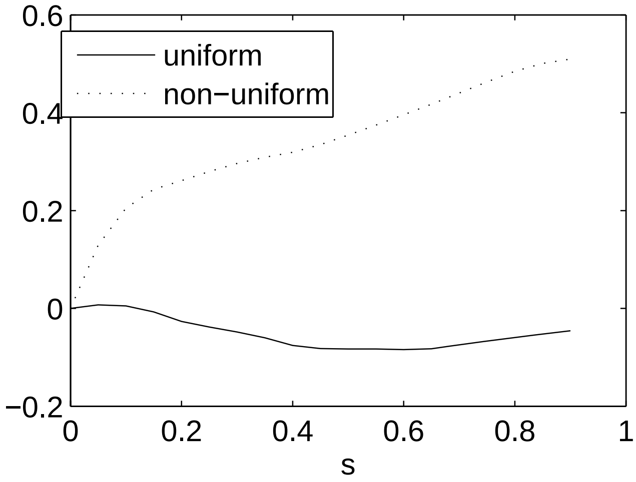


Fig. 6: $\widehat{\Delta_u(s)}$; the uncertainty effect from repeated, uniform (solid) and non-uniform (dotted) shocks, for different protected area sizes s, under the 'skewed' probability distribution.

Table 3 also indicates the change in value, denoted V^*, at the optimal reserve size s^*. These figures indicate that the change in value is relatively very small, more or less negligible, in all cases where the shocks are spatially uniform. This suggests that reserves has little value if there is no correlation between the protected area and the probability of exogenous shocks to the stock level. The implication is that reserves should only be implemented when some additional protection is available, typically in terms of environmental factors, such that the protected substock is less vulnerable to exogenous shocks.

Finally, a few words about the effect from considering the 'skewed' distribution. The uncertainty effect from repeated shocks is shown in Figure 6. The most immediate observation from the figure is the nature of the results from the 'skewed' probability distribution, particularly in the case with uniform shocks. While the effect responds in a more or less monotonic fashion to the reserve size under symmetric distributions, it seems more unpredictable under the asymmetric distribution. Further, while the result from non-uniform shocks mostly seem to amplify the already existing trend from the results from the uniform shocks under symmetry, this amplification is not evident in the same manner under an asymmetric probability distribution (cf. Figure 5).

Discussion: Issues and suggestions

As far as single initial shocks goes, the effects found in this analysis are accurate. When it comes to repeated shocks, the analysis builds upon one obviously fragile assumption. The assumption that each new shock has the same effect on the value of the resource implies that the system has returned to the steady state before each new shock. There are several issues related to this. One is how much interest the steady state warrants. It would be interesting if one could explore the effects of exogenous shocks independent of the steady state stock level as the initial condition. The number of possible initial conditions then becomes very large. It could be interesting to look at the time the system takes to return to the steady state without further shocks. Under repeated shocks, the system is not guaranteed to return to the steady state, and it would only be temporary anyway. The question then is how far ahead one have to look before movements are insignificant to the present value of the fishery.

Another issue of the implied assumption of return to the steady state is how big the induced error is. Note that when the mean of the probability distribution of the shocks is nonpositive, the expected effect from a shock to the steady state is negative for any area size. Let ϵ_0 be the 'expected shock'; a representative shock that corresponds to the expected effect from a shock with a given probability distribution. ϵ_0 has to be negative, since positive shocks has a positive effect. The expected profit in the fishery is reduced upon the expected shock and is given by $\Pi(x^* + \epsilon_0)$. As the system moves towards the steady state after the shock, the profit from the fishery also moves towards the profit level in the steady state, $\Pi(x^*)$. Let the change in value from the shock over one time period, which is the aggregated change in profit, be denoted Δ_1. Upon a new shock at the beginning of the second period we get an overlap in the effect from the shocks under the implied assumption. This is illustrated in Figure 7, where the 'overlap' effect is denoted Δ_∞. There is one conclusion to draw from this. The effects related to repeated shocks reported in this paper includes the 'overlap' effect and is thus an *upper bound* on the true effect. This holds independent of the return to steady state assumption, given that shocks to smaller stock levels has smaller expected effects, which follows readily from the concavity of the value function. Still, a more accurate calculation of the effect from shocks would accrue from backing out the 'overlap' effect and sum over Δ_1 instead of $\Delta(s) = \Delta_1 + \Delta_\infty$, as above. ($\Delta_1$ and Δ_∞ both depend on s,

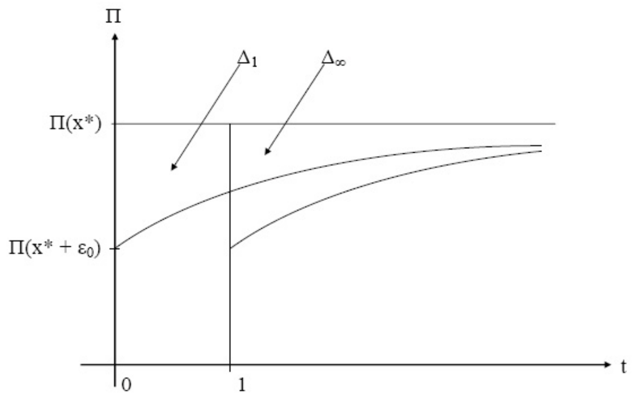


Fig. 7: Illustrating the 'overlap effect'.

of course, the argument is just omitted here.)

Finally, the alternative measure $\Delta_s(s)$ poses further challenges. Given that each new shock has the same effect upon the value of the fishery, one could sum over Δ_1, where Δ_1 is now illustrated in Figure 8. Here, $\Pi(x^* + \epsilon_0)$ is the profit from the shock ϵ_0 which corresponds to the expected effect from a shock with no reserve, while $\Pi_s(x^* + \epsilon_0)$ is the profit with a reserve of size s. In Figure 8, the short run effect on profit from a shock is smaller in the presence of a reserve, while the long run steady state profit level is higher without a marine reserve (which is consistent with the findings in Kvamsdal and Sandal (2008)). Note that this implies that the area corresponding to the 'overlap' effect Δ_∞ changes sign at some point in time. This complicates the procedure of backing out the 'overlap' effect. However, there is still a problem with summing over Δ_1, as it ignores how the effect from repeated shocks may change since the stock level before each new shock changes. The ultimate resort from this problem is averaging over repeated simulated realizations of repeated shocks.

Conclusions

Two types of shocks has been examined; spatially uniform and non-uniform. These successively corresponds to perfect correlation and independence of uncertainty between substocks, and hence, recruitment. Hannesson (2002), among others, consider the same correlation relationships. However, the actual correlation is more likely to be somewhere in between these extrema, and there is no

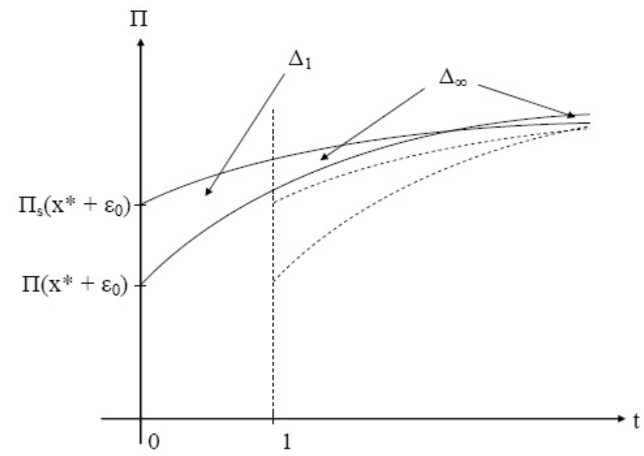


Fig. 8: Suggesting how to assess simulations.

reason to believe that there is any simple relationship, *e.g.* linear, between the outcome from the extremities to a more realistic correlation. This is particularly disturbing given the unpredictable pattern that emerges from considering an asymmetric probability distribution of the shock size (Figure 6), which probably is a realistic assumption for exploited stocks. For example, assumptions in Lauck et al. (1998) and Sumaila (2001) imply asymmetric distributions. Further research into these things is necessary.

The failure of reserves to produce significantly favorable outcomes under uniform shocks (Table 3) implies that a rather strict set of requirements applies before reserves should be implemented. These are (i) a sufficient degree of uncertainty (the value-added declines rapidly as the variance of the probability distribution, and hence the uncertainty, declines), (ii) an asymmetric probability distribution, and (iii) a less than perfect correlation between the substock levels or the probabilities of shocks in the different areas. Further requirements are that the reserve must be of an appropriate size, and that the interaction between the substocks, *i.e.* migration, must be sufficiently 'high' (Sumaila (2001)). The latter ensures that the reserve functions as a buffer against shocks, and not only as a safe sanctuary for the fish, as the density of fish will be smoothed at a meaningful rate.

Appendix

The β probability distribution is defined on the domain $[0,1]$, and is given by

$$P(x) = \frac{(1-x)^{\beta-1}x^{\alpha-1}}{B(\alpha,\beta)}$$

where $B(\alpha,\beta)$ is the β function, given by

$$B(\alpha,\beta) = \frac{(\alpha-1)!(\beta-1)!}{(\alpha+\beta-1)!}$$

The mean of the distribution is given as $\mu = \dfrac{\alpha}{\alpha+\beta}$. The variance is given by $\sigma^2 = \dfrac{\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)}$. Note that in this paper, the domain is $[-0.9, 0.9]$. Hence, the probability distribution is mapped to this domain with the appropriate linear transformation. The advantage of the β distribution which I exploit is that it is confined to a finite domain. Thus, it is not necessary to be concerned with normalization or heavy tails resulting from a truncated distribution.

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