# LETTER

# A theory for optimal monitoring of marine reserves

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## Abstract

Monitoring of marine reserves has traditionally focused on the task of rejecting the null hypothesis that marine reserves have no impact on the population and community structure of harvested populations. We consider the role of monitoring of marine reserves to gain information needed for management decisions. In particular we use a decision theoretic framework to answer the question: how long should we monitor the recovery of an over-fished stock to determine the fraction of that stock to reserve? This exposes a natural tension between the cost (in terms of time and money) of additional monitoring, and the benefit of more accurately parameterizing a population model for the stock, that in turn leads to a better decision about the optimal size for the reserve with respect to harvesting. We found that the optimal monitoring time frame is rarely more than 5 years. A higher economic discount rate decreased the optimal monitoring time frame, making the expected benefit of more certainty about parameters in the system negligible compared with the expected gain from earlier exploitation.

## Keywords

Conservation, cost, marine reserve, monitoring, optimization, profit.

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## INTRODUCTION

Marine-protected areas (MPAs) have become a popular approach to managing small-scale marine fisheries (Nowlis & Roberts 1999; Dayton *et al.* 2000; McClanahan & Mangi 2000), and the number of no-take reserves has increased in recent years (Allison *et al.* 1998). However, in the global effort to establish marine reserves (Lubchenco *et al.* 2003), some fundamental questions remain largely unresolved. One issue that has received little attention is the application of decision theory to help design monitoring strategies that aim to assess effectiveness of a marine reserve. Gerber *et al.* (2002) argue that, in practice, it is virtually impossible to achieve an optimal reserve design because of parameter and model uncertainty. Monitoring is therefore critical to assess effectiveness of a reserve and allow prompt modification of management and monitoring strategies.

Previous approaches to designing monitoring programmes have sought to maximize statistical power, but not to optimize a management objective (Thompson & Mapstone 2002). Monitoring of marine reserves has thus far addressed biological parameters in most cases (Russ & Alcala 1996) although a number of recent studies have incorporated monitoring of socio-economic effects (e.g. Dixon *et al.* 1993). To date, monitoring studies have

provided evidence of increased density of fishes inside and outside of reserves (Alcala 1988; Bohnsack 2000), and in some cases increases in fishing yields (Gerber *et al.* 2003; Willis & Millar 2005), but have not addressed effectiveness in terms of the enhancement of sustainability and population persistence. There is some evidence that spawning biomass, abundance and average size of fishes may increase in marine reserves (Rowley 1994; Halpern 2003). In a meta-analysis of 19 studies describing the effects of marine reserves on overall fish abundance and species inside and outside reserves, Côté *et al.* (2001) reported an insignificant trend towards increase of overall species abundance in reserves when compared with adjacent unprotected areas. Perhaps not surprisingly, a study that considered individual fish species found that only commercially important species increased in abundance significantly inside the reserve (Mosquera *et al.* 2000). An uncharitable view of the literature on monitoring marine reserves would argue that existing research on marine reserves has allowed us to successfully reject the null hypothesis that fishing does not kill fish.

Monitoring is the systematic acquisition of information over time. In the context of marine reserves, monitoring is the process of collecting information about state variables (e.g. abundance, size or vital rates) at different points in time

for the purpose of detecting changes in those variables. Many marine reserves are established with the primary purpose of fisheries management, for example, to halt the population decline of target species in a heavily fished area (Bohnsack 1998; Neubert 2003). The efficacy of a reserve in achieving its objectives is assessed in monitoring studies that evaluate whether the expected recovery of fished stocks can be demonstrated from time series data (Russ & Alcala 1998; McClanahan & Mangi 2000; Trexler & Travis 2000).

Monitoring programmes for marine reserves are often intended to evaluate the efficacy of a reserve in fulfilling the goal of optimizing a fishery's sustainable yield. Ideally, the results of such a monitoring programme should directly inform future management decisions. For example, monitoring could give us the information needed to change the location or management of reserves. However, despite the widespread recognition of the importance of monitoring as well as the importance of adaptive management to enhance marine reserve efficacy (e.g. Murray *et al.* 1999; Agardy *et al.* 2003), we are not aware of any studies that quantitatively place monitoring results in the context of possible changes in management or monitoring regimes (but see Obura *et al.* 2002 for an anecdotal example of monitoring leading to an adjustment of management). To date there has been little discussion in either scientific or management arenas of appropriate triggers for a change in management and possible actions.

This paper provides a decision theory framework for designing a monitoring programme for a marine reserve to maximize the profit of an adjacent fishery. We propose a theory of optimal monitoring where the purpose of monitoring is solely to make the best decision for management, and where the costs of monitoring and losses of the fishery because of fishing closure are considered explicitly. Using an example where the habitat of a heavily exploited fish species is now completely reserved, we answer the question: how long is it worth monitoring to improve estimates of optimum design?

## A THEORY FOR OPTIMAL MARINE RESERVE MONITORING

While there is a large body of literature on how to best design a monitoring programme to maximize the probability of detecting a change (statistical power) and some guidance on how to set relevant error rates, there are few tools available to assist managers in determining the level of resources that should be invested in monitoring relative to those that should be invested in management. The answer to this question is determined by evaluating the likely benefit to management of the information gained through monitoring and whether this is sufficient to warrant the cost of management (Field *et al.* 2004).

Consider the example of comparing reserves of differing size and location, where monitoring is clearly important. Here, the question is how to make decisions about the monitoring (timing, frequency, intensity, cost, state variables) and how to incorporate monitoring results into management. In this way, marine reserves can be viewed in the framework of adaptive management (either passive or active) where managers are learning about the system (Walters 2001), in this case the adequacy of a reserve. Monitoring results then allow managers to refine models and modify their actions, such as modifying the reserve, increasing enforcement, seeking other causes of population decline that the reserve cannot address or changing the monitoring regime. In many cases, marine reserves approach active adaptive monitoring because it takes the form of an experiment with controls, before-treatment data and sometimes replication (Fig. 1). Relevant aspects of adaptive monitoring to marine reserves include:

(1) Monitoring is linked to management actions. For example, if some benefit does not accrue from creation of the reserve, then the reserve could be altered in shape, size, or location, other reserves could be created, or the reserve abandoned.

(2) The system state is linked back to monitoring, so that aspects of monitoring may change as the system changes. Monitoring may be reduced once an objective has been achieved or it may be increased as the system approaches some threshold where management action may be required. If a marine reserve is not expected to show an effect for several years then monitoring may initially be of lower intensity. Such sporadic monitoring will obviously not describe the pattern of change following establishment of a reserve, but might be more cost-effective.

(3) The optimal effort invested in the monitoring regime is determined by a trade off between the cost of monitoring and the benefit gained through increased knowledge that leads to better management.

Monitoring programmes should measure state variables that can guide management action when compared with management objectives. The often-reported enhancements to fish stocks in terms of biomass and age structure may not necessarily provide a basis for management decisions. What is of greater interest is the effect size and whether that meets model predictions or stakeholders' expectations. In particular, appraisal of the reserve needs to balance benefits of the reserve such as increased biomass or fish size against the cost of imposing the reserve and the cost of monitoring. Below we illustrate the application of these principles using an example problem.
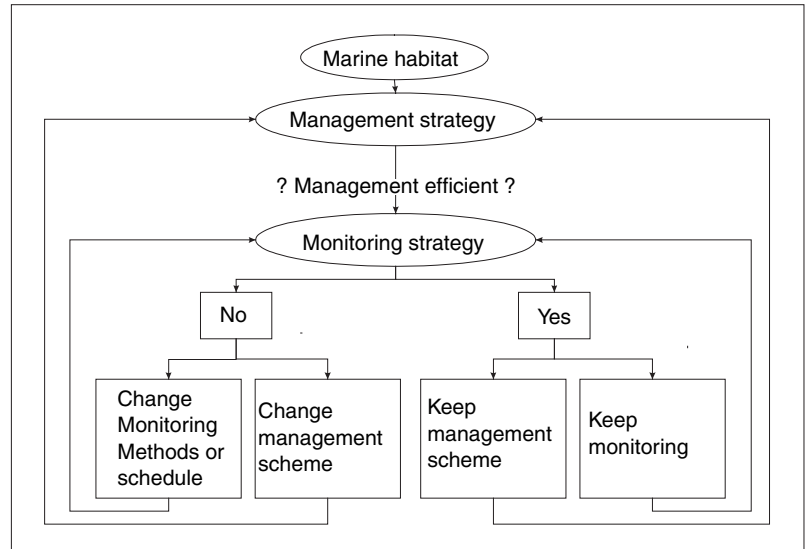
**Figure 1** Schematic diagram showing the integration of adaptive management and adaptive monitoring in a decision framework of marine reserve management aiming to achieve optimal efficacy with regard to cost and benefits (ecological and socio-economic).

## EXAMPLE PROBLEM

To illustrate how decision-theoretic approaches can integrate monitoring with management for marine reserves (see Field *et al.* 2004 for a terrestrial example), we consider a situation where a regional fish stock has collapsed to a low level and use a simple population model to identify the optimal fraction of a habitat to be protected in a reserve. Nested within this model, we incorporate a second optimization model describing the influence of monitoring data on parameter estimates of the target species. We illustrate how decision-theoretic approaches can help to optimize the combination of the cost of monitoring, the opportunity cost of keeping the fishery closed and the cost or benefit of taking management action (such as reopening a fraction of habitat to the fishery). In this example, we ask how many years of monitoring data will maximize our net expected benefit?

Our objective is to maximize long-term profit for the reserve system accounting for costs of monitoring and the profit from the harvesting. To do so, we focus on the common scenario of monitoring changes in abundance and survivorship of fish following the establishment of a reserve. We extend this approach to illustrate how typical monitoring data can be used to influence management decisions by modelling a situation in which a previously unprotected site is closed to fishing. With a reserve protecting 100% of available habitat, we allow the fish stock to recover from harvesting for $n$ years, while monitoring every year until a decision is made about what fraction of area is opened for the fishery. We make the simplifying assumption that all mature fish are harvested in the unprotected area each time-step (therefore recruitment comes only from the reserve)

and that recruited fish mature in the time-step between harvests. The long-term annual harvest of fish will vary with the fraction of the total area that is reserved. Harvest is maximized for an intermediate level of protection in which an optimal fraction of habitat is protected ($f^*$; Fig. 2). Following Gerber *et al.* (2002), our underlying population model is a two-patch Ricker model for a single species reserve,
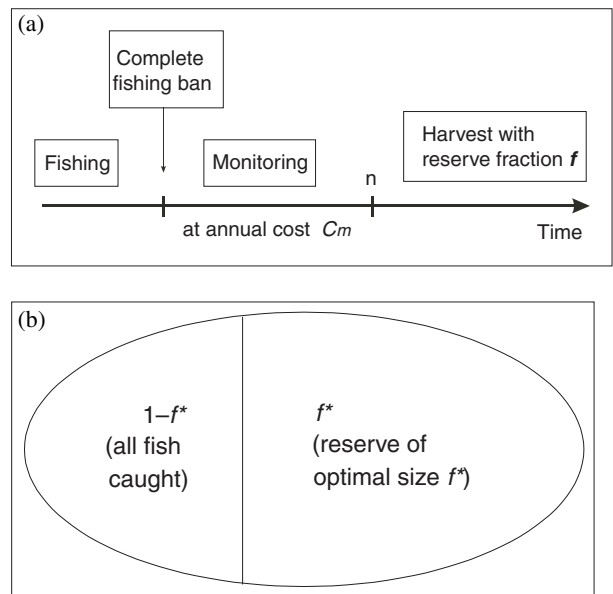


**Figure 2** (a) Timeline for fisheries and monitoring assumed in model and (b) schematic representation of optimal reserve size $f^*$, where all mature fish are harvested in the unprotected area each time-step.

$$N_{Rt} = N_{Rt-1}e^{r\left(1-\frac{N_{Rt-1}}{K}\right)}f \tag{1}$$

$$N_{Ut} = N_{Rt-1}e^{r\left(1-\frac{N_{Rt-1}}{K}\right)}(1-f) \tag{2}$$

where, $N_{Rt}$ and $N_{Ut}$ represent abundance in the reserve and unprotected areas, respectively, at time $t$, and $r$ represents the intrinsic rate of population increase. The equilibrium number of fish in the reserved area (such that $N_{Rt} = N_{Rt-1}$) is,

$$N_R^* = K\left(1+\frac{\ln(f)}{r}\right) \tag{3}$$

Substituting $N_R^*$ into eqn 2 provides the equilibrium number of fish in the harvested area,

$$N_{Ut}^* = K\left(1+\frac{\ln(f)}{r}\right)\frac{1}{f}(1-f) \tag{4}$$

This equation provides the annual profit (in terms of the number of harvested fish) under the assumption that all fish are harvested. Differentiating $N_{Ut}^*$ with respect to $f$ and setting the derivative equal to zero provides the optimal fraction of the area to reserve [$f^*(r)$]. The solution depends only on $r$ and satisfies the implicit equation

$$r = 1 - f^* - \ln(f^*) \tag{5}$$

Thus, the optimal reserve size can be identified based on the population growth rate (Fig. 3).

While the simplicity of this solution is theoretically satisfying, in practice we never have a perfect estimate of the population growth rate ($r$), which determines optimal reserve size. In this circumstance, the key question is: when is our estimate of $r$ sufficiently precise for making a decision about reserve size? To address this question, we consider the long-term profit $P$, accounting for the absence of harvest while we are monitoring and the cost of monitoring. For every additional year of monitoring the precision of our
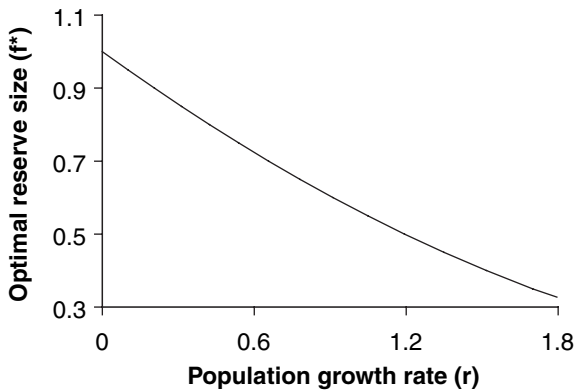


**Figure 3** Relationship of optimal reserve size $f^*$ and population growth rate $r$.

estimate of $r$ improves, hence providing a better estimate of $f^*$ and increasing long-term yield. However, improving our precision of $r$ by monitoring for each additional year incurs monitoring costs and lost revenue from the fishery. Thus, the expected long-term profit ($P$) is the discounted expected yield once fishing is initiated minus the discounted costs (at discounting rate $\delta$) of monitoring for $n$ years,

$$P = -C_m\left[\frac{1-(1-\delta)^{n+1}}{\delta}\right] + C_f\frac{E(Y)(1-\delta)^n}{\delta} \tag{6}$$

where, $C_m$ is the annual cost of monitoring, $C_f$ is the price of fish, and $E(Y)$ is the expected yield. The expected long-term profit ($P$) depends on how many years we monitor before harvesting ($n$) through the discounting of the yield, but also the expected value of the yield.

To identify optimal monitoring time frames, we find the value for $n$ that maximizes eqn 6. In particular, we calculate the expected annual yield (number of fish in the unprotected area for a given value of $f$) by integrating $N_{Ut}$ over the possible values of $r$, and defining how the uncertainty in $r$ depends on $n$. To do this, we assume that the estimate of $r$ is normally distributed with a mean $\mu_r$ and standard error $\sigma_r = \frac{SD}{\sqrt{n}}$, where SD is the standard deviation of each annual sample of $r$. Of course, analysis of abundance time trend does not actually produce independent estimates of $r$ for each year. Rather, learning is a 'Kalman filter' autocorrelated process and may take longer than predicted assuming independent estimates of $r$ (Walters 2001). Variation in each annual sample arises from the combined effects of natural variation and sampling error. Thus

$$E(Y) = \int K\left(1+\frac{\ln(f)}{r}\right)\left(\frac{1-f}{f}\right)p(r|n)dr \tag{7}$$

where, $p(r|n)$ is the probability density function of the normal distribution

$$p(r|n) = \frac{1}{\sqrt{2\pi\sigma_r^2}}\exp\left[-(r-\mu_r)^2/2\sigma_r^2\right] \tag{8}$$

The integration of eqn 7 is over all non-negative values of the integrand to account for the impossibility of having negative yields. Because there is no closed-form solution for eqn 7, we used numerical integration in MATHEMATICA (Skeel & Keiper 1993) to calculate $E(Y)$. We assumed the optimal fraction reserved ($f^*$) would be set based on the mean of the estimate of $r(\mu_r)$ using eqn 5. With our estimate of $r$ for three representative life histories for marine species (low, medium and high growth rates), we explored the importance of uncertainty in $r$ in identifying optimal time frames for monitoring.

Growth rates for marine fisheries species vary considerably, for example, between $r = 0.08$–$0.44$ for a suite of temperate marine fish larvae (Paradis & Pepin 2001).

**Table 1** Parameter values and combinations used in the analysis (eqns 6–8)

| Parameter | Values considered |
| --- | --- |
| Population growth rate ($r$) | 0.2, 0.8, 1.5 |
| Optimal reserve size ($f^*$) | 0.4, 0.65, 0.9 |
| Carrying capacity ($K$) | 10 |
| Annual cost of monitoring ($C_m$) | 0 |
| Market price of fish ($C_f$) | 10 |
| Discounting rate ($\delta$) | 0.01, 0.04 |

FISHBASE hosts data for the intrinsic rate of population growth ($r_m$) for available data (for example, for the Humphead Wrasse *Cheilinus undulatus* $r = 0.52$; Fishbase 2005). Caddy (2004) provides details for growth rates for finfish in the categories of very low productivity ($r < 0.05$), low productivity ($r = 0.05$–0.15, for example, sharks and orange roughy), medium productivity ($r = 0.16$–0.5, for example, cod, hake and plaice) and high productivity (> 0.5, for example, sardines and anchovies).

We parameterized our model with a range of plausible values (Table 1) based on available data and evaluated optimal monitoring over a 10-year time horizon for decisions concerning monitoring. While this represents a short time horizon from a population dynamics perspective, resource managers rarely have the luxury of planning beyond 10 years. Furthermore, we assumed that costs of monitoring were insignificant compared with the money to be made from the fishery ($C_m = 0$). In cases where monitoring costs are greater, the optimal time frame of monitoring would be shorter. We used two levels of economic discounting, 1 and 4%; the latter rate is commonly used for economic analyses (NOAA 1997) while the former emphasizes benefits of increasing the long-term yield. It is important to note that for simplicity we did not consider the conservation benefits of the reserve and only consider its benefits in terms of providing a source of harvested fish. However, we also maximized the expected profit of the fishery subject to the constraint of having a sufficiently high probability that the fishery was sustainable [*Pr(Sustainable)*, i.e. the probability of having a positive equilibrium yield was greater than a prescribed amount].

## RESULTS

Our results illustrate the benefits of monitoring a marine reserve to maximize the expected long-term profit. First, we note that the expected yields were higher for fast-growing species that require a small fraction of the habitat as a reserve (Fig. 4a). The expected yield increased faster with each year of monitoring when the growth rate was less variable [compare coefficient of variation (CV) of 0.3 with 0.8].

The long-term profit was maximized for monitoring programmes ranging between 3 and 7 years for a discounting rate of 1%, depending on the precision of monitoring achieved (Fig. 5). The optimal number of years to monitor was largely determined by the precision of the monitoring method, where a more accurate estimate of the growth rate resulted in a shorter monitoring time frame (CV = 0.3). Less accurate estimates of $r$ required a longer period of monitoring after the establishment of the reserve. For each set of values for $r$ and $f^*$, the magnitude of the long-term profit did not change substantially with varying CV. However, long-term profit dramatically decreased with the size of the reserve area. The size of the reserve generally did not influence optimal monitoring, except for monitoring methods with low accuracy (CV = 0.8).

Increasing discount rates decreased the optimal period of monitoring until at a discount rate of 4% it was not most efficient to monitor at all (Fig. 5). This occurred because the benefit gained from the increased knowledge was not sufficient to compensate for the forgone profit from not harvesting the fishery. This implies that there is little benefit to learning, and the decision about the optimal size of the reserved area should be made without collecting additional data. However, if the problem is constrained by a requirement that we should be reasonably sure that the fishery is sustainable, then the optimal number of years to monitor will sometimes be determined by this constraint rather than the maximum expected profit (Fig. 4b). For example, if we need to be almost certain that the fishery is sustainable (e.g. the probability of having a sustainable fishery must be close to 1 before permitting harvesting), then 10 or more years of monitoring may be required.

## DISCUSSION

Marine reserves are often established to manage fisheries threatened by decreasing yields and unsustainable harvests. The ideal MPA project would combine management schemes and associated monitoring based on knowledge of the natural system. In turn this information should inform predetermined trigger values for changes in management and monitoring. While such a scheme would be ideal, establishing a marine reserve, regardless of whether it is optimally designed, is often viewed as an achievement in itself, and resources for monitoring are usually very limited. Furthermore, monitoring rarely serves the needs of managers as it is often conducted by scientists who put their research interest before the managers' needs (Hodgson 2000).

Our work departs from the many previous studies that model marine reserves by explicitly identifying the link between monitoring and management, while most other theory seeks to identify some 'optimum solution' for reserve configuration. In practice we rarely have the luxury of
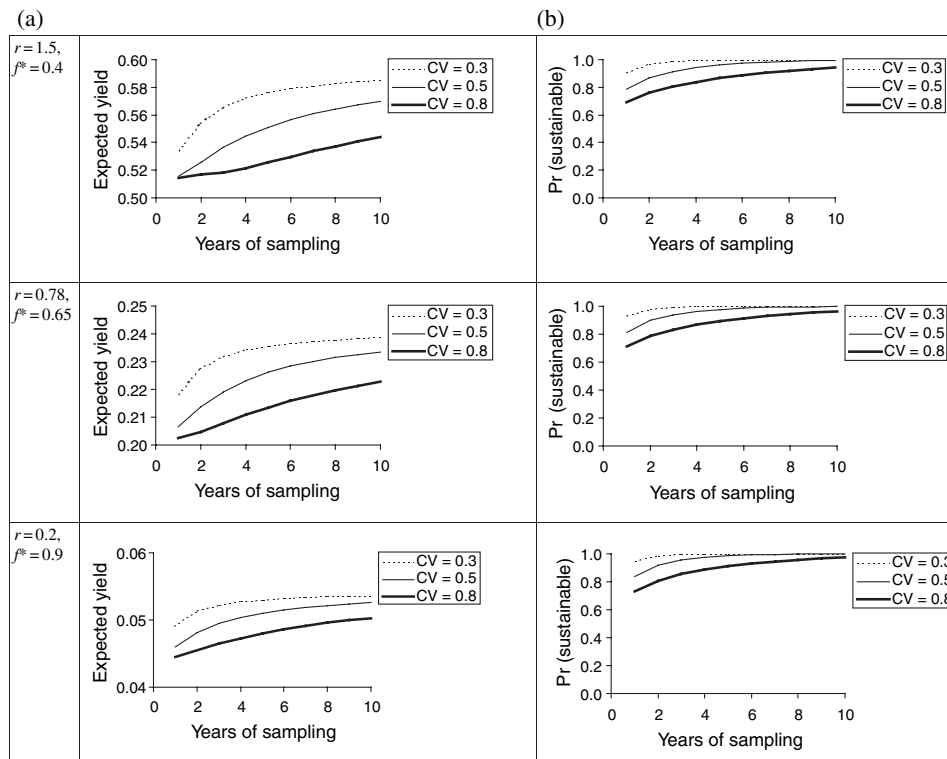
**Figure 4** (a) Relationship between the number of years monitoring *n* and the expected yield *E(Y)* for three combinations of population growth rate *r* and optimal reserve size *f \** and a varying degree of accuracy; (b) relationship between the number of years monitoring *n* and the probability that the fishery is sustainable [*Pr(Sustainable)*] for three combinations of population growth rate *r* and optimal reserve size *f \** and a varying degree of accuracy.

information required for the establishment of an optimally designed reserve. Thus, while optimal reserves are possible in theory, a more practical question might be, how much data do we need to establish a reserve of a given size? Our model shows that optimizing the cost of a combined programme of monitoring and management can guide how best to apply a limited amount of funds. In our example, for a discounting rate of 1%, our model showed an optimal monitoring time frame of between 3 and 7 years, which is coincidentally the time frame that is often recommended by managers, for example in Egypt (Galal *et al.* 2002), or Papau New Guinea (Jones *et al.* 2004). This result is in contrast to the widespread view within some management organizations that monitoring should be conducted indefinitely (e.g. Pomeroy *et al.* 2004). It is important, however, to keep in mind that there is generally a delay between changes in juvenile abundance (e.g. spillover of larvae and juveniles) and appearance of these fish in the harvestable population. Thus, time required for management experiments is the optimal monitoring time frame described above in addition to this delay. For species where this total time is markedly long, the appropriate discount rate (and whether to proceed at all with monitoring) may need to be reconsidered.

It is important to remember several of our major assumptions when applying this approach to a real world problem. First, we assumed that we are managing a single species fishery. Interactions between species and the selective targeting of the fishery for more valuable fish species have not been considered in our model. Most fisheries species undergo a life cycle in two phases: the larval and adult phase. In our model we assume that during the larval phase, larvae spread across the habitat patch homogeneously. It is likely that larval distribution occurs heterogeneously in reality, and recent studies have shown that a significant percentage of larvae self-recruit to their birth-patch (Jones *et al.* 1999; Swearer *et al.* 1999). Thus, it would be problematic to apply our model directly to large habitat patches where larval may spread be less efficiently into the fished area. Our assumption is that larval recruitment includes not just settlement but also survival to legal size adults within the period between settlement and fishing. In most fisheries it would be difficult to determine the exact time of spawning and settlement even if the target species matures within a year. Finally, we assumed that the cost of monitoring in our numerical example was zero relative to the value of the fishery. In reality, the cost would
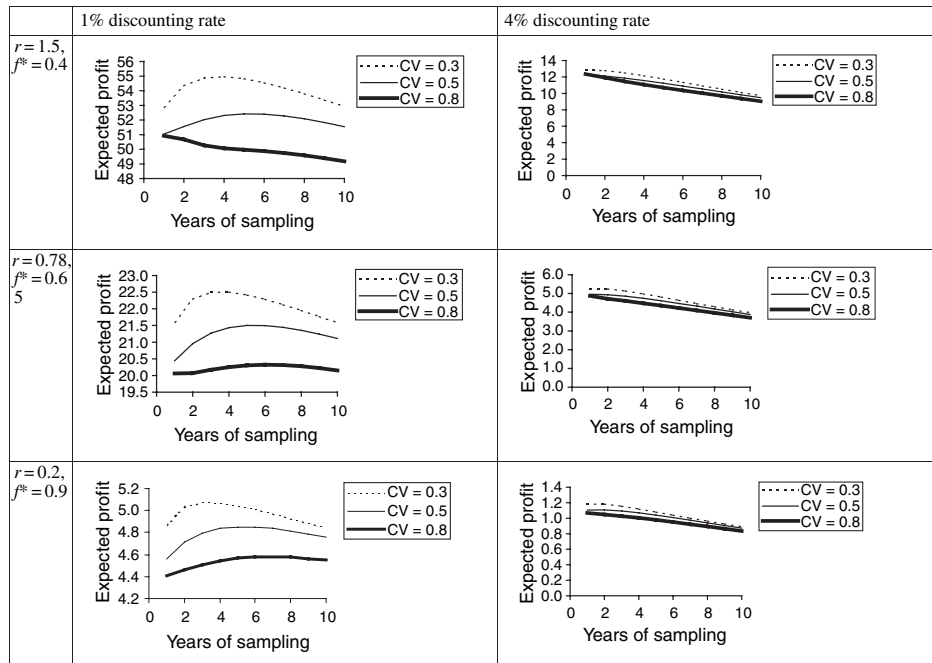
**Figure 5** The expected profit $P$ for different number of years monitoring for three combinations of population growth rate $r$ and optimal reserve size $f^*$ and the discounting rates $\delta$ of 1 and 4%.

often likely to be proportional to the precision of data collected, as it would translate into employing more surveyors or spending more time to monitor. Cost of monitoring is difficult to estimate owing to differences in how MPAs are administered and funded in different parts of the world.

Our model of learning assumed that only a single parameter was unknown, which was the mean growth rate of the population in the absence of density dependence. In reality, a much larger suite of parameters will be unknown. Indeed, we assume that the variation in the population growth is known, whereas in reality, this will also be uncertain. Given that the optimal time frame of monitoring depends on this parameter (Fig. 5), it is likely that uncertainty in this parameter and our ability to learn about it will also influence the optimal monitoring time frame. We chose the simplest possible case study for illustrative purposes, and focused on the mean population growth rate because it has a direct influence on the optimal size of the reserve (Fig. 3) and, therefore, it is likely to have the greatest influence on the optimal number of years to monitor.

Furthermore, monitoring and fishing are not mutually exclusive. An important next step will be to investigate scenarios in which fishing commences before monitoring stops. In fact, fishing provides contrasts that can improve learning about $r$. It will also be important to examine the interaction between $r$, high discount rates and the optimal reserve size. Where few data on $r$ are available, optimal

reserve size will be largely determined by the uniform prior distribution for $r$. Because of the nonlinear relationship between $r$, yield and reserve size, the reserve size chosen may not be centred on the $f$ corresponding to the midpoint of the range of $r$. Whatever value of $f$ is favoured by the prior, it will perform better for some values of the true $r$ than others. This probable asymmetry is partially real and partially a complication in interpreting these analyses. It will be important to examine this to identify the optimal value of $f$ that would be calculated if no data on $r$ existed. An additional consideration is that more information about the parameter $r$ can be obtained during recovery from low abundance than at equilibrium, so learning might be faster initially than later. A stock is likely to be at low density throughout its habitat when a reserve is first established, and especially when $r$ is small may not have recovered when fishing starts. Initial catches (except the first see below) may be smaller than equilibrium levels. The older the age at maturity, the more important this transition to equilibrium is likely to be. The result would probably be to extend the period during which not fishing is the best policy.

To maintain fisheries at a sustainable yield and quantify the quota for the next season is a major reason for monitoring in fisheries (Beukers-Stewart *et al.* 2003). Improving the precision in the estimation of $r$ increased the expected maximum yield at a faster initial rate. This corresponds to greater certainty in the permitted sustainable maximum yield, resulting in higher catches to the benefit of

the fishery. If monitoring costs are considered, the maximum long-term profit is achieved earlier for high CVs, indicating that high precision in data collection, while more expensive, can have the benefit of shorter monitoring programmes.

There are no previous guidelines of what the triggering parameters for adaptive management should be, how they should be quantified prior to the onset of a monitoring project, and how or when a monitoring programme should be altered to react to observed trends. Our paper provides a theoretical evaluation of the interaction between management, monitoring, fisheries benefits and cost in the context of an optimally managed marine reserve. Some major lessons can be drawn from this for the design of an integrated adaptive management scheme coupled with monitoring.

(1) Monitoring should inform management to trigger a change of management or monitoring. Optimal outcomes can be achieved if management, monitoring and trigger values are defined before the start of a programme.
(2) The cost of monitoring, monetary benefits for users, the cost of management and economic discounting of profit should be considered.
(3) The type of data gained from a monitoring programme is important to long-term benefits, as it may be efficient to invest in a more expensive method that yields more accurate data.
(4) It may be more efficient to cease monitoring once a predetermined degree of certainty that a fishery is sustainable is achieved, thereby saving resources that could be allocated elsewhere.

There are benefits of MPAs other than profits to fisheries. Benefits to the public in the form of recreational opportunities, conservation of biodiversity, ecosystem functionality and tourism income have not been considered in our analysis, but are important in a real world application. A monitoring programme may aim to assess the ability of the MPA to maintain these values. In this case, the optimal time frame and type of monitoring would be different than that described here. Long-term monitoring may also be beneficial for raising community awareness, or gaining information about ecosystem processes. For all of these goals, the important question ultimately is: 'why monitor marine reserves'? Because a proper definition of objectives and actions associated with a monitoring programme will increase its benefits and help managers determine the optimal allocation of resources to monitoring.

## ACKNOWLEDGEMENTS

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