Conservation Letters
A journal of the Society for Conservation Biology
Open Access

LETTER

Minimizing the Short-Term Impacts of Marine Reserves on Fisheries While Meeting Long-Term Goals for Recovery

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Keywords
Marine conservation; Sasi; coral reef; livelihood; fishery economics; ecosystem model; marine protected area.

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Received
12 February 2014
Accepted
10 July 2014

Editor
Edward T. Game

doi: 10.1111/conl.12124

Abstract

Marine reserves are a promising tool for recovering overfished ecosystems. However, reserves designed to rebuild profits in the long-term may cause short-term losses—a serious issue in regions where fisheries are key for food security. We examine the tension between the long-term benefits of reserves and short-term losses, using a multispecies model of coral reef fisheries. Reserves designed to maximize long-term profits caused significant short-term losses. We model several policy solutions, where we incrementally increased either: the number of months per year that the reserve is closed to fishing; the size of the reserve; or the number species protected within the reserve. Protecting species sequentially, starting with the most valued species, provided the best outcome in the short-term with the most rapid recovery of profits. Solving the dilemma of meeting short- and long-term goals will ultimately improve the effectiveness of marine reserves for managing fisheries and conserving ecosystems.

Introduction

Small-scale fisheries are an important part of many economies and form an essential part of many livelihoods in low-income regions (Sadovy 2005). Further, their dollar value understates their social and cultural importance. Small-scale fisheries are an important source of protein for people with little opportunity for alternative employment (Sadovy 2005) and form an integral part of many coastal cultures (Johannes 1981). These fisheries typically target multiple species, and resources for monitoring, management, and enforcement are often limited. Consequently, many of the world's small-scale fisheries are overfished and recovering them would benefit both fisheries and the conservation of marine ecosystems (Newton *et al.* 2007; Costello *et al.* 2012). No-take marine reserves have frequently been proposed as a strategy to recover small-scale fisheries (Roberts *et al.* 2005; Fox *et al.* 2012). In overfished fisheries, effectively enforced marine reserves can improve fisheries harvests and profits in the mid to long-term (e.g., Russ *et al.* 2003; Goñi *et al.* 2010), and help to recover overfished populations (Lester *et al.* 2009).

Implementing marine reserves is challenging in practice, in part due to opposition from fishers (Smith *et al.* 2010; White *et al.* 2013b). Immediately after implementation, marine reserves reduce harvest and potentially profits, because fishers lose fishing grounds (Smith *et al.* 2010). The fishery will not see improved profits, from the spillover of adult fish and increased larval supply, for at least several years after implementation. A short-term outlook may predominate in many small-scale fisheries, so the long-term benefits of recovery will be heavily discounted by individual fishers (Clark 1973; Teh *et al.* 2013). Fishers may also be unable to afford a short-term loss in harvest (e.g., Van De Geer *et al.* 2013). Excessive short-term losses create incentives for increased rates of illegal fishing within reserves. Thus, the long-term benefits of reserves to fisheries and ecosystems may never be realized.

Approaches to planning marine reserves have tended to focus on either avoiding short-term profit losses or maximizing long-term benefits. Short-term losses caused by reserves are a measure of likely opposition to reserve implementation (Smith *et al.* 2010). For instance, the popular software, Marxan, attempts to minimize the opportunity cost of a reserve system (e.g., Klein *et al.* 2009; Watts *et al.* 2009), a measure of the short-term profit loss (White *et al.* 2013b). Short-term opposition is dissipated in the long-term, when the benefits of spillover become apparent (Smith *et al.* 2010). In contrast to software like Marxan, population models have been used to examine how reserves affect profits in the longer term (e.g., Walters *et al.* 2007; Kaplan *et al.* 2009; Rassweiler *et al.* 2012). Short- and long-term perspectives are not commonly considered together (White *et al.* 2011). This lack of integration has hindered the science of reserve management, because the ideal reserve design for fisheries would balance trade-offs among short-term losses, social acceptance, and long-term benefits.

Here, we examine the trade-off between short-term losses of profit and long-term gains in fisheries profit from marine reserves. Our case study is a multispecies coral reef fishery, chosen because it reflects typical properties of small-scale fisheries—coral reef fisheries are multispecies; many are small scale, overfished and lack strong top-down management; and there is widespread interest in using reserves to recover fisheries (e.g., White *et al.* 2014). The short-term costs of reserves may be reduced by gradual implementation (Holland & Brazee 1996), so we examine three plausible policy options for gradually implementing a reserve. These include gradually increasing: reserve size, the number of species that are protected inside a reserve, and the number of months per year of reserve closure. A precedent for each of these options exists in formal and informal fishery management. In some Pacific Islands, artisanal fishers agree to temporary closures for specific species to allow recovery of stocks and increased harvests at a future time (e.g., McLeod *et al.* 2009). For industrial fisheries, gradual reductions in quotas and area-specific closures on particular species have been commonly used to assist in recovering overfished species (e.g., Smith *et al.* 2008). We propose ways these management strategies can be used to ease the short-term burden placed on fisheries by marine reserves.

Methods

Fish population model

We model three species groups that are typical of coral reef fisheries. They are coral trout (meso-predators), parrotfish (grazers), and snapper (invertivores) (e.g., Teh *et al.* 2005; Bejarano *et al.* 2013). We chose these groups because: they are typical of coral reef fisheries; their harvest may be increased by marine reserves; their relative values vary; and they can be selectively targeted so our policy option for targeting a subset of species is feasible.

We used a discrete-time (monthly time-step) model, where the populations were size-structured and divided between reserved and fished patches (see Appendix S1, Figures S1 and S2). The model represented an area of $\sim$10,000 km^2, although, all parameters are scalable to larger or smaller areas. Population dynamics were based on those commonly employed for models of marine reserves and included an increase in larval production with fish biomass (e.g., Holland & Brazee 1996; Rassweiler *et al.* 2012). We assumed larvae were distributed evenly across patches. Density-dependent compensation (termed "fish density compensation") occurred between settling larvae, and the maximum recruitment of juveniles was proportional to a patch's area. A fraction of the resident fish left and entered each patch, each month, in proportion to reserved/nonreserved area and a movement rate parameter. Thus, a reserve could benefit fisheries through larval and adult spillover: reserves held a larger biomass of spawning fish, which increased their relative contribution to the larval pool and fish could grow inside reserves then move to fished areas. The model assumed that within a patch, fish were evenly distributed. For the three species, the relationship between harvest and effort varied because of species-specific susceptibility to fishing and their relative abundances in the wild (Appendix S1, Figure S1).

Fishery revenues were summed across the three species accounting for their relative values per kilogram. Annual revenue per species was calculated as the biomass of a species harvested multiplied by its relative value. Harvest costs were set so cost per kilogram of capturing a species was greater when its density was lower and profits were zero when biomass reached a prescribed level of its unfished amount (Table S1, White *et al.* 2008).

Effort was constant over time. The initial conditions ("status-quo") for all simulations were at the equilibrium age structure without a reserve. When a reserve was created, fishing ceased in that area and all fishing effort was reallocated to nonreserved areas, although we also ran simulations where effort was not reallocated.

We presented three metrics for the economic effects of a reserve policy: (1) The most severe annual loss in profits, calculated as the greatest negative difference between annual status quo profits and profits with the reserve policy at any time after reserve implementation. The severe profit loss represents the greatest annual profits a fishery is deprived by reserves. (2) Number of years required until profits stabilized at their maximum. (3) Net present value, discounted over a 50-year period post-reserve implementation, which reflects net loss or gain from a reserve policy. The discount rate was varied from 0 to 50% per annum. Values of less than 10% represent typical public discount rates (Teh *et al.* 2013). Private discount rates can be greater than 10% for fishers who only care about profits in the next year or two (Teh *et al.* 2013). Reserve policies that have a high net present value for discount rates >10% may be useful for reducing opposition from fishers with a short-term view, but may be inefficient in the long-term.

Scenarios

First we examined a base scenario where a single reserve is implemented in a single event. We examined the trade-off between the annual loss and the long-term (equilibrium, approximately 50 years postreserve implementation) profits, while varying the total effort level and reserve size. We also find the reserve area (termed A_{opt}) that maximizes economic yield at equilibrium (P_{opt}), calculated as the annual profits summed across all species at equilibrium, for a given level of effort. The optimal was found through simulation using a golden ratio search algorithm. Effort was expressed relative to the effort at the maximum economic yield (F_{MEY}).

For subsequent scenarios, we focused on an overfished fishery, because our main aim was to examine recovering overfished populations. For overfishing, effort was set at $2 \times F_{MEY}$ and profits were 58% of their maximum.

We examined three policies for gradual reserve implementation, which reduced the annual loss from reserves. For all policies, the eventual target is a reserve of area A_{opt}, with an equilibrium revenue of P_{opt}. Thus, only the transient dynamics differed between the policies. Each policy had a different control parameter, which we varied to affect the duration required until the reserve was fully implemented. The policies were:

(1) Gradually increase the number of months per year that are closed to fishing. The number of closed months that were added each year was varied. For this policy, we explored two plausible responses of fishing effort to partial closures. First, effort was constant in each month. Second, there was a compensatory increase in effort in open months, which accounted for the missed months of fishing. In open months the fishing mortality in the reserved area was increased in proportion to the ratio of open and closed months. As a reference point, we also ran scenarios where the number of months closed per year is fixed. This management policy is similar to existing traditional management practices in several Pacific Island nations (Cohen & Foale 2013).

(2) Gradually increase the area reserved each year, at a constant rate, until the reserve area reaches A_{opt}. We varied the rate of reserve area increase. Fishing effort was redistributed to the open patch as reserve area increased.

(3) Gradually increase the coverage of species protected by a reserve of fixed size. We ran simulations where the species were protected sequentially, in three different orders: from high to low valued; low to high valued; and mid-, low-, high-valued. The high valued species had the slowest recovery rates from overfishing. We varied the number of years between declaring protection of each species. This scenario assumes that selective fishing of each species is possible. For instance, parrotfish can be caught using spears, whereas snapper and coral trout could be caught selectively in a line fishery.

Sensitivity analyses

We determined the effect of ecological and economic contexts on the effectiveness of the policies by varying the level of overfishing, relative values of the fish species, and fish density compensation ratios. Higher compensation ratios reflect greater resilience to fishing pressure and should increase recovery rates. We also explored policy outcomes when the values per kilogram of the species were varied and their movement rates were higher. The incremental species policy may force fishers to switch to species they are not familiar with harvesting. We represented the costs of switching by modeling a temporary decline in catch efficiency (of up to 30%) for nonprotected species in the incremental species policy (Appendix S1). Finally, we modeled a declining fishery, where the aim of reservation was to "rescue" the fishery from overfishing (Appendix S1). For the declining fishery, we only present the net present value. The time to maximal profits was not relevant, because a declining fishery may temporarily exceed the long-term profits achievable with reserves.

Results

Trade-off between short- and long-term profits in a single reserve

First, we analyzed the scenario with a single reserve that was implemented in a single event. Reserves increased equilibrium profits from the status quo if effort outside reserves exceeded the optimum (Figure 1a). There was greater improvement in profits for greater levels of effort. In the short-term, reserves always resulted in an annual loss in profits (Figure 1b). Relative annual losses were similar regardless of the effort level. Therefore, in

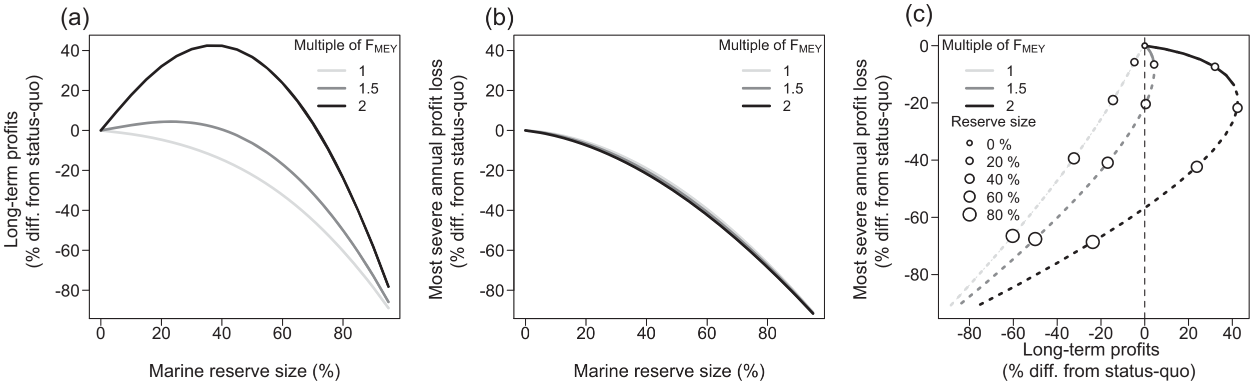

Figure 1 Effect of increasing reserve size on long-term and short-term profit losses (decrease in profits from status quo). (a) Marine reserve size (% of total area) and long-term profits at different fishing mortality rates (relative to the long-term optimal). (b) Marine reserve size and the most severe profit loss after reserve implementation (curves for the three fishing mortality scenarios overlap). (c) Trade-off between long-term profits and loss, circles indicate reserve size.

overfished fisheries, a trade-off emerged between equilibrium profit and annual loss: reserves up to intermediate sizes increased equilibrium profits, but at the same time had a more severe annual loss (solid lines, Figure 1c). Large reserves were inefficient for fisheries, because they had both a more severe annual loss and lower equilibrium profits (dashed lines, Figure 1c). Similarly, a trade-off exists between the annual loss and equilibrium profits when comparing policies that temporarily close reserves each year (Figure S2).

Policy scenarios

The gradual implementation policies all softened the annual loss when compared to implementing a reserve in a single event (Figure 2). However, they also required longer for the equilibrium profit to be reached. In further analyses, we varied the control parameter for each policy, which varied the time taken to implement the full reserve of area A_{opt} (Figure 3).

The effect of the incremental months policy on profit depended on whether there was effort compensation in open months (Figure 3a, b). If effort did not increase in open months, the incremental months policy had similar outcomes to the incremental size policy (Figure 3c, d). If fishing effort compensated for closed months by increasing in open months, annual losses were always about 30%, regardless of the time taken to implement the reserve.

When species were added incrementally to a reserve, profits at a time depended on the order that the species were added (Figure 2). Reservation of the valued species first had the least severe annual loss if less than 11 years was taken to implement the full reserve (Figure 3e, f).

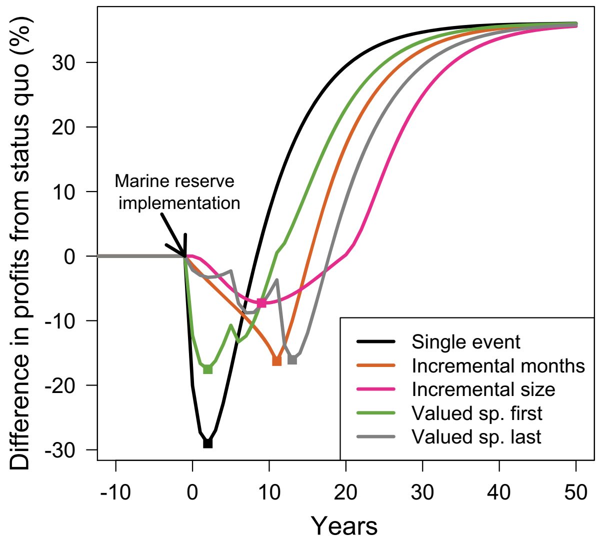

Figure 2 Difference between profits with a reserve policy and profits without a reserve (status quo) over time for the main reserve implementation policies. The annual loss metric for each policy is indicated by square points. The policy control parameters for delay in implementing the reserves were chosen to represent a range of short-term losses and times to reach the optimal.

Annual losses were low, because even a small recovery in the high valued species was sufficient to offset profit losses from the other species. For longer delays in implementation, the other incremental species policies had only minor annual losses, because recovery of low valued species was sufficient to supplement fishery profits. The valued species first policy always had equal or shorter time to reach the equilibrium profits, because the most valued species was also the slowest growing.

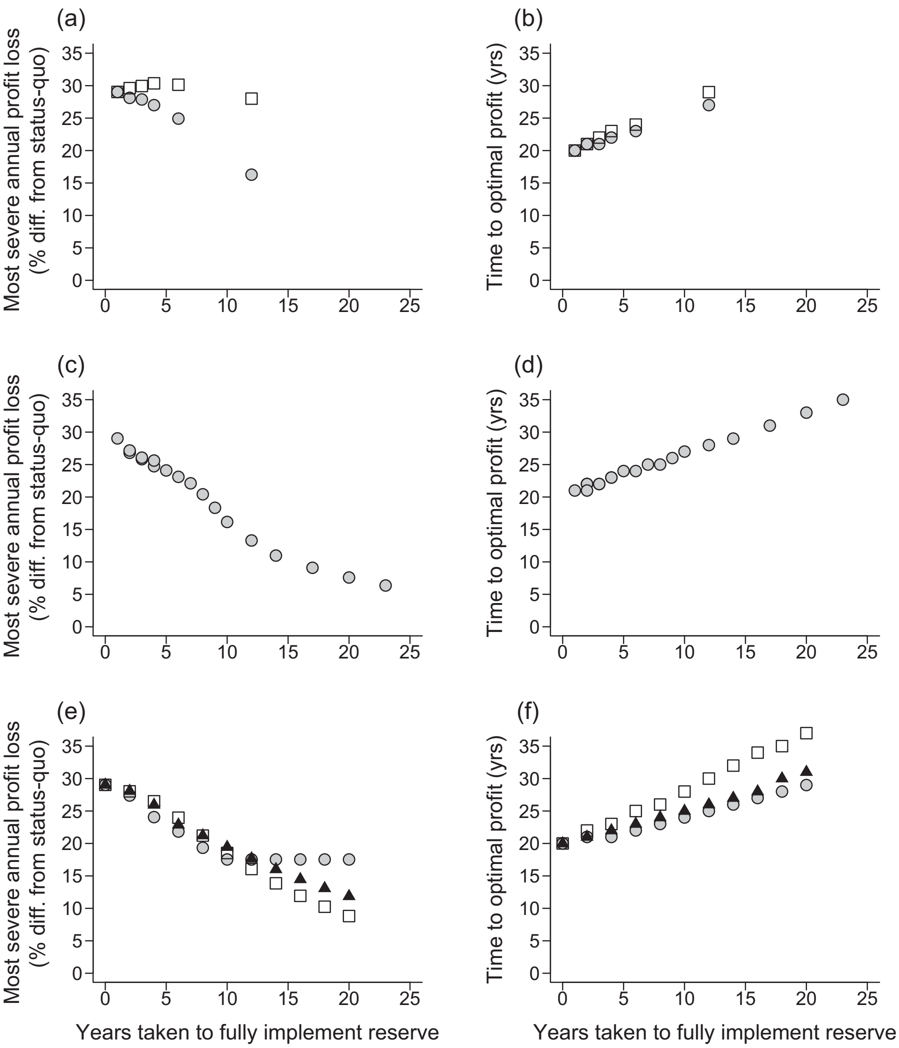

Figure 3 Effect of varying the number of years taken to implement a reserve on (a, c, e) time until the maximal harvest is reached and the (b, d, f) maximum short-term profit loss for three incremental reserve policies. For each policy, a policy specific control parameter is varied to increase the number of years taken to implement the reserve. Shown are policies for (a, b) incrementally increasing the number of months per year reserved, without effort compensation (grey circles) and with effort compensation (white squares); (c, d) incrementally increasing the size of the reserve; and (e, f) incrementally adding species to the reserve with the most valued species added first (grey circles), the middle valued species added first (black triangles), and the most valued species added last (white squares).

Comparison of policies

For a given policy, varying the control parameter results in a trade-off between softening the annual loss and reaching the optimal profits in the shortest time (Figure 4a). The trade-offs can be used to compare the policies. Policies that result in a smaller annual loss, but reach the optimal faster, are the most efficient (i.e., lower to the left in Figure 4a). A policy for implementing a reserve in a single event had the most severe annual loss but the fastest time to reach the optimal profit.

The valued species first policy had the fastest recovery to optimal profits over the range of annual losses from the most severe (28% loss) to ~18% loss (Figure 4a). For less severe losses, but longer recovery times, the incremental size policy was superior. The incremental months and size policies had similar trade-offs. The incremental months policy was the least efficient if there was effort compensation.

For all the policies, there was also a trade-off between the annual loss and the net present value over 50 years discounted at a rate of 5% (Figure 4b). The trade-offs

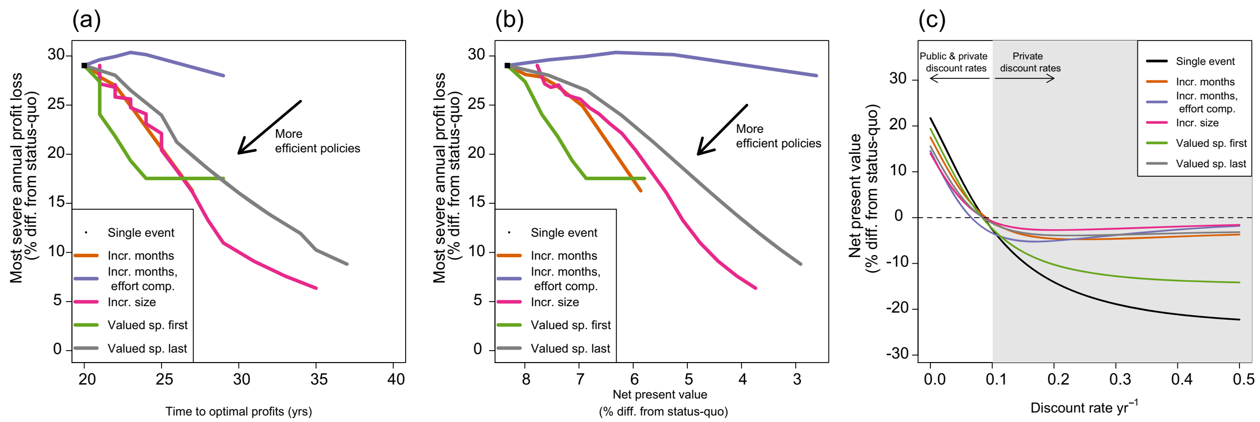

Figure 4 The effects of different reserve implementation policies on (a) the trade-off between profit loss and time to reaching optimal harvest and (b) profit loss and net present value, discounted at 5% (c) the net present value for different discount rates. In (a) and (b), points lower to the left are the best performing policies, because they have smaller losses and, reach the optimal faster (a) or have a higher net present value (b). In (c), the control parameter parameters were chosen so that time to reach optimal harvest was ∼30 years.

were similar to Figure 4a, indicating that the net present value was largely determined by the duration to reach the optimal profits.

For discount rates less than 9%, all reserve policies had a higher net present value than the status quo (Figure 4c). Net present value was highest if the reserve was implemented in one event. For fishers with private discount rates greater than ∼10%, net present value was less than status quo for all policies. The valued species last and incremental size policies delayed annual losses, so their net present value was higher for high discount rates when compared to the other policies.

Changing key ecological and fishery parameters affected the relative advantages of the policies (Table 1). In particular, if species had similar values per kilogram, the trade-offs for the incremental species policies became similar. Interestingly, with equal values or a high value on parrotfish, the superior policy was reserving the fast-growing species first (parrotfish), because its rapid recovery within reserves provided benefits to the fishery sooner. Counterintuitively, if catch efficiency declined temporarily after protecting species, the incremental species policies had a more rapid recovery to the optimal profits. Declines in catch efficiency meant biomass and profits recovered more rapidly.

Implementing a reserve in a declining fishery could slow the decline so that it stabilized at P_{opt}. Similar to the main analysis, if discount rates were low (e.g., 1%) implementing the reserve in one event had the highest net present value (Figure S3). For high private discount rates (e.g., 15%), the net present value was less than the status quo and more gradual implementation had a relatively higher net present value.

Discussion

Alternative reserve designs are often evaluated in the context of their short-term opportunity costs (e.g., Klein *et al.* 2008) or their long-term benefits to fisheries once fish biomass has recovered (e.g., Walters *et al.* 2007; Kaplan *et al.* 2009). We have quantified the trade-off between these goals for one case study. Quantifying trade-offs between goals at different time scales is important for informing stakeholders and policy makers about the impacts of recovery measures. Confusion about the impacts of reserves to fisheries at different time scales may lead to inefficient reserve designs and create unnecessary opposition and economic hardship, particularly if different stakeholders (e.g., conservationists and fishers) are comparing benefits at different time scales (White *et al.* 2013b). For instance, the low discount rates used for public policy suggest that reserves are beneficial, whereas high private discount rates suggest fishers will oppose reserves in preference for the status quo.

Flexible policies for implementing reserves can soften profit losses for fisheries while still reaping the long-term benefits, but at the cost of requiring longer to recover profits. The delay in recovery meant that for reasonable public discount rates (<10%) the net present value was greatest if the reserve was implemented in one event. The importance of reserve impacts at different time scales will depend on the social and management context. For instance, in fisheries with strongly enforced rights-based management, fishers are more likely to be motivated by maximizing profits over longer time spans (Grafton *et al.* 2006). In such instances, policies that maximize net present value may be the most useful, such as reserving

Table 1 Summary for the effects of changing key parameters on the outcomes

Parameters changed	*Short-term, long-term trade-off*	*Policy comparison*	*Net present value*
Higher initial level of overfishing	Reserves have greater benefits in the long run	Similar, although all scenarios require longer for optimal to be reached	Discount rates up to 25% are still profit positive
Equal values of all species	Similar to base scenario	Incremental species policies have very similar outcomes to each other	The policy where the fast growing species are protected first has a higher net present value, because recoveries are more rapid and make up for lost profits sooner
Highest value for parrotfish (species with the fastest population growth)	Similar to base scenario	Reserving parrotfish first is always the superior policy, because profits recover most rapidly	Similar
Higher fish density compensation ratio	Optimal reserve size was smaller and long-term benefits were smaller, reduced annual loss	Similar	Similar
Higher movement rates	Optimal reserve size is greater, annual losses are similar.	Similar, however, incremental months policy with effort compensation gets better (although it is still the worst).	Similar
No aggregation of effort when reserve is declared	Similar, although annual loss declines linearly with increased reserve area	Similar, although, incremental months policy with effort compensation gets slightly better	Similar, discount rates up to ∼18% are still profit positive.
Higher cost of fishing	Annual loss is greater, long-term profit is lower	Annual loss is higher for all policies, policy order similar	Net present value is lower, but policy order is similar
Short-term decline in catch efficiency for incremental species policy	Same as base scenario	Incremental species policies improve, because biomass recovers more rapidly	Similar to base scenario, scenarios with decline in catch efficiency have slightly higher NPV for low discount rates and slightly lower NPV for very high discount rates

the most valued species first. In other fisheries, such as those where fishers are forced to maintain unsustainable levels of fishing to repay debts (e.g., Cinner *et al.* 2009), avoiding severe profit losses is critical. Therefore, policies such as gradually increasing reserve size will be best.

Another solution to avert profit losses from marine reserves is to help fishers diversify their livelihoods (e.g., part-time work in the tourism sector, Campbell *et al.* 2006; Sala *et al.* 2013). Importantly, it often takes at least a decade to install the support, training, and opportunities for diversifying livelihoods (Campbell *et al.* 2006). The policies we suggest here are a rapid option for implementing a reserve system, while avoiding severe profit losses to fishers. Such policies may then allow time to implement longer-term strategies aimed at diversifying livelihoods and reducing fishing capacity.

An important caveat to our findings is the cost of enforcement and management. This can be considerable for marine reserves and can be greater if implementation of reserves takes longer (McCrea-Strub *et al.* 2011). The more complex policy arrangements we modeled here may have additional costs over those for a standard marine reserve (Wilen 2004) and are more difficult to enforce. For instance, partial spatial closures for select species may be more expensive and time-consuming to enforce, and are only practical in selective fisheries. Further, the incremental months policy was only effective if there was no compensatory increase in effort, so without additional effort regulations this policy is much less effective than incrementally increasing the size of a reserve. Some management costs may be overcome by using policies that align with traditional management methods, such as Sasi law (e.g., McLeod *et al.* 2009). Further research should quantify the relative management costs of the reserve policies we propose and establish their feasibility in different social contexts.

The relative benefits of the policies we propose are sensitive to the ecological, cultural, and economic context of a fishery. For instance, reserving the highest valued species first achieved the most rapid recovery of long-term profits for a given amount of short-term loss. If the values of species were similar, then reserving parrotfish first was preferable, because species with fast growth recover to their equilibrium state most rapidly (White *et al.* 2013a). The values of different coral reef species can vary considerably across places and time (e.g., Mumby *et al.* 2012; Bejarano *et al.* 2013). Considering local preferences for fishery species is therefore important for choosing a policy for reserve implementation.

We suggest an iterative process of assessment and communication with stakeholders for moving forward with practical application of our proposed reserve policies (Fox *et al.* 2012). Future studies should use geographically realistic models to compare reserve policies. Such models can assess the influence of biological traits we did not consider here, such as patterns of larval dispersal (e.g., Costello *et al.* 2010), and economic factors, such as displacement of fishers to unfamiliar fishing grounds (Van De Geer *et al.* 2013). The next step is then to propose the different policy scenarios developed here to fishermen in a reserve planning exercise. An iterative process helps to communicate the potential benefits and impacts of reserves to fishing communities (Leisher *et al.* 2012). Fisher surveys would help to narrow the uncertainty on fishers preferences for short-term costs versus long-term benefits, which is context dependent (Teh *et al.* 2011). Updated discount rates can then be used to more accurately quantify trade-offs between fishers preferences and goals for long-term recovery and ultimately generate more acceptable reserve proposals to fishers.

The short-term impacts of reserves to fishers may hinder their implementation and recovery of fisheries. Flexible policies for reserve implementation can provide options with lower short-term costs that are potentially more acceptable to fisheries. Ultimately, this will help increase the effectiveness of marine reserves in recovering overfished fisheries.

Acknowledgments

CJB was funded by a UQ Postdoctoral Fellowship. PJM and SA were funded by a Laureate Fellowship to PJM, a NERP grant, a Pew Fellowship, and European Union 7th Framework program (P7/2007-2013) under grant agreement No. 244161. We are grateful to M. Saunders, E. Game, and three anonymous reviewers for helpful comments.

Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Appendix S1. Equations and detailed methods for the fishery model.

Table S1. Parameter values for the fishery model.

Figure S1. Species-specific susceptibility to fishing pressure.

Figure S2. Effect of regular monthly closures on equilibrium profits and the most severe annual profit loss.

Figure S3. Net present value when the reserve policies are implemented in a declining fishery.

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