Marine reserves switching under uncertainty

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Abstract

This paper analyses a fisheries management strategy, marine reserves switching, in which a non-fishing area is created, removed, or rotated from one site to another according to economic criteria through time. Using a dynamic optimisation framework under uncertainty, with the different fish dispersal processes, the optimal switching strategy and density distributions of the biomass, harvest, and net profit are simulated and compared under different management scenarios. This study will provide a decision and modelling framework for the design of marine reserves to achieve desired management goals.

Keywods: bioeconomic model, fisheries management, marine reserves, uncertainty

JEL Classification: Q22

1 Introduction

In the last two decades, marine reserves have received increased attention as a strategy to solve management failures in fisheries There is the theoretical and empirical evidence of various biological and socioeconomic benefits from closing a fishing ground.[1] For example, reserves will; 1) increase spawning biomass and population abundance; 2) improve habitat quality; 3) have a positive spillover effect from the reserves to the fishing ground; 4) generate less variables in biomass and catch; 5) stimulate knowledge in marine biology and oceanography; 6) enhance tourism and recreational activities while protecting cultural heritage; and 7) act as an insurance against catastrophe such as recruitment failure and unexpected variations in marine environments. Also, while it has been more controversial whether reserves can increase the harvest (Holland and Brazee, 1996, Hannesson, 1998, Hannesson, 2002 and Sumaila, 1998), previous studies find that reserves can increase economic payoffs if fish stocks are overfished (Pezzey, Roberts, and Urdal, 2000 and Rodwell and Roberts, 2004), the opportunity cost of closing the area is low compared to the benefit from continuing to harvest fish stocks in the area (Sanchirico and Wilen, 2001 and Sanchirico et al., 2006), or a large negative shock is realised. Acting as a hedge against the shock, reserves can increase economic payoffs from fisheries even if harvest and effort levels are optimally controlled (Grafton, Kompas, and Ha, 2006).

While a number of studies show various advantages of creating non-fishing areas, the optimal design of marine reserves, such as location and duration of fishing closures, is still controversial. Where we should set the non-fishing area and how long the area should be closed in order to maximise the return from fishing while conserving fish stocks. Compared to the issue of whether we should create reserves, it has been less discussed how we should manage or design marine reserves, especially in a dynamic optimisation framework.[2] For example, most previous research has focused on permanent fishing closure, and only a little has analysed the temporary fishing closure as well as switching strategy, in which the protected area is switched over time.[3] Thus, it is still not clear whether reserves should be fixed at a single

[1]There are a large number of previous studies on marine reserves. Comprehensive literature reviews are provided by for example Guenette, Lauck, and Clark (1998) and Grafton, Kompas, and Schneider (2005)

[2]Compared to literature in economics, the design of marine reserves are well discussed in biology and ecology. For example, see the special issue in *Ecological Applications* in 2003.

[3]An exception is Hilborn and Walters (1992). They briefly discuss rotational harvest strategies for stock

site or should be flexibly shifted corresponding to the changes in environment.

To address this issue, this paper analyses a fisheries management strategy, marine reserves switching, in which a non-fishing area is created, removed, or rotated from one site to another according to economic criteria through time. The marine reserves switching strategy is more flexible in the management than the fixed reserve and the no-reserve strategies, since it encompasses the other two. The switching strategy allows to fix a reserve at a single site and also allows not to create reserves. Moreover, it would be more attractive from a socioeconomic perspective, since it will not permanently close a specific fishing ground. However, it is important to note that the decision process could be complicated. In the switching strategy, the decision - whether a non-fishing area is created, removed, or switched and the timing of the switching - depends on various factors; the relative stock abundance in each harvested and reserve populations, the transaction cost of switching the reserve, the fish dispersal process, the site specific ecological and economic environment, and the uncertainty in the stock-recruitment relationship as well as the realisation of large negative shocks. The research questions addressed in this paper are specifically: in which timing should the non-fishing area be switched through space; and what is the consequence of employing the switching strategy; i.e., to what extent do the density distributions of the biomass, harvest, and net profit change between different management scenarios?

The paper is organised as follows. In the next section, a bioeconomic model for the marine reserve switching is developed with two stochastic terms (growth uncertainty and negative shock) and with various fish dispersal processes. The computational method to solve the model is also discussed in this section. In Section 3, the optimal proportion of the switching period and the density distributions of the biomass, harvest and net profit are simulated and compared under different management scenarios. The sensitivity analysis is presented in Section 4, and the last section provides concluding remarks.

recoveries (p.530), but a formal theoretical analysis has not been conducted.

2 The model

2.1 Biological model

Space: Space in the marine environment is modeled by discrete patches. Each patch represents a unique fish habitat and the size is determined by the carrying capacity. Assume that each patch has a same size, the distance from one another is identical, and they are interconnected by the transfer function $T_{ij}(\mathbf{x})$, where $\mathbf{x}$ denotes the vector of the fish stock, and $i, j \in N$ is the site index over n dimensional space, $N = \{1, 2, \ldots, n\}$. In this paper, in order to make the problem tractable, we assume that the marine environment is zoned into three sites ($n = 3$).

Population dynamics: Time is discrete, indexed by $t \in T$, and $T = \{1, 2, \ldots\}$. The carrying capacity is normalised to unity ($K^i = 1$) such that the biomass x_i represents density rather than the actual weight of fish. The population dynamics in site $i \in N$ at time t are modeled as follows:

$$\begin{aligned} x^i_{t+1} &= x^i_t + z^{gi}_t r x^i_t (1 - x^i_t) + \sum_{j}^{j \neq i} T_{ij}(\mathbf{x}) - z^{si}_t x^i_t - h^i_t, \text{ if site } i \text{ is open; and} \\ x^i_{t+1} &= x^i_t + z^{gi}_t r x^i_t (1 - x^i_t) + \sum_{j}^{j \neq i} T_{ij}(\mathbf{x}), \text{ if site } i \text{ is closed.} \end{aligned} \tag{1}$$

where x^i_t is the fish stock in site i. If site i is a fishing ground, the fish stock is exploited by the harvest level $h^i_t > 0$, while $h^i_t = 0$ if the site is a reserve. The second term represents the density dependent fish growth function with the intrinsic growth rate r. The third term is the fish transfer function that will be further discussed in the later subsection. The terms z^{gi}_t represents stochastic variations in the fish growth at site i (growth uncertainty), and z^{si}_t is a large negative shock that are relative to the fish stock. Assume that negative shocks are only realised in fishing grounds due to human activities.

Uncertainties: The growth uncertainty is specified as $z^g = 1 + (2u - 1)\epsilon$, where u is a uniformly discretised grid. The term ϵ determines the size of variations, and it lies between 0 and 1, indicating from 0 per cent to 100 per cent variations. It is assumed that z^g follows a Markov process with the same transition probabilities between each state. The large negative shock z^s is specified as,

$$z_t^s(\omega_t) = \begin{cases} 0 & \text{if } \omega_t = 1 \text{ (shock is not realised)} \\ \alpha & \text{if } \omega_t = 2 \text{ (shock is realised)} \end{cases} \tag{2}$$

Thus, if the indicator variable ω_t is 2 at time t, then the negative shock is realised, otherwise there is no shock. The size of the negative shock is proportional to the stock level that is determined by a parameter α. The frequency of the negative shock follows the transition matrix,

$$\begin{pmatrix} 1-\tau & \tau \\ 1 & 0 \end{pmatrix} \tag{3}$$

where τ is the probability of the shock arrival in each period. It is assumed that the shock cannot occur sequentially.

Transfer functions: The transfer function captures the characteristics of the fish flow from one site to another. This paper considers three different dispersal processes; 1) fully integrated; 2) sink-source; and 3) spatially linear process. Assume that the fish flow depends on the relative density of the biomass between three sites. Hence, fish flows from a highly dense to a lower dense area. For the fully integrated process, every site is interconnected each other:

$$\forall i, j \in N,\ i \neq j,\ T_{ij}(\mathbf{x}) = m(x_j - x_i) \tag{4}$$

where m is the transfer coefficient. Note that, since the fish outflow from i to j is equivalent to the inflow to j from i, $T_{ij} = -T_{ji}$. For the sink-source process, suppose that site 1 is the source and the other two sites, 2 and 3, are the sink. Thus, the fish flows from site 1 to 2 and to 3, but not for the opposite directions, and there is no interconnection between 2 and 3:

$$\begin{aligned} i = 1,\ j \in \{2,3\}\ ,\ T_{ij}(\mathbf{x}) &= \min\left\{m(x_j - x_i), 0\right\};\ \text{and} \\ T_{ji}(\mathbf{x}) &= \max\left\{m(x_i - x_j), 0\right\} \end{aligned} \tag{5}$$

For the spatially linear process, sites are arrayed in a line, and each site is interconnected only with an adjacent site. Suppose that site 1 and 3 are the two edges, and site 2 locates between 1 and 3:

$$\begin{aligned} i \in \{1,3\},\ j = 2\ ,\ T_{ij}(\mathbf{x}) &= m(x_j - x_i);\ \text{and} \\ T_{ji}(\mathbf{x}) &= m(x_i - x_j) \end{aligned} \tag{6}$$

2.2 Economic model

The fishery manager's objective is assumed to maximise the discounted economic returns from harvesting the fish stock over an infinite time horizon. The future returns are discounted with the discounting factor $\beta \in (0,1)$. Suppose that $\Gamma \subseteq N$ is a set of the sites that are open for fishing, and then, the net profit at time t is defined as:

$$\pi_t = p(h_t)h_t - \textstyle\sum_{i\in\Gamma} c(x_t^i)h_t^i \tag{7}$$

where h is the total harvest, $p(\cdot)$ is the inverse demand function and $c(\cdot)$ is the cost function. The inverse demand and cost functions are, respectively, defined as:

$$p(\cdot) = \bar{p}h_t^{-1/\delta} \text{ and } c(\cdot) = \bar{c}/x_t^i \tag{8}$$

where δ is the constant price elasticity of the demand, and $\bar{p}$ and $\bar{c}$ are parameters. Note that $p_h < 0$, $p_{hh} > 0$, $c_x < 0$, and $c_{xx} > 0$. Hence, the demand curve is downward sloping and strictly concave. The cost is a function of the fish stock, and the total cost decreases as the population density increases.

The harvest level depends on a reference point, or a rule sometimes referred to as the feedback control; thus h_t^i is a proportional to the each period's stock level in the fishing ground. The simplest specification is;

$$h_t^i(x_t^i) = \begin{cases} \theta x_t^i & \text{if } i \in \Gamma \\ 0 & \text{if } i \notin \Gamma \end{cases} \tag{9}$$

Therefore, the fishery manager faces a discrete choice problem to maximise the discounted economic returns over a infinite time horizon. There are four choices, thus the manager decides either close one of the fishing grounds or open all sites. Suppose that site $o \in N$ is initially set as a reserve and site $i, j \in N$ are open for fishing; i.e., $\imath, j \in \Gamma$ and $o \notin \Gamma$, and then the value function is defined as:

$$\begin{aligned} V(\mathbf{x_t}, \mathbf{z^g_t}, \mathbf{z^s_t}) = \max \Big\{ & \pi(x^i_t, x^j_t) + \beta \mathbb{E}_0 V(\mathbf{x_{t+1}}, \mathbf{z^g_{t+1}}, \mathbf{z^s_{t+1}}), \\ & \pi(x^i_t, x^o_t) - \kappa + \beta \mathbb{E}_0 V(\mathbf{x_{t+1}}, \mathbf{z^g_{t+1}}, \mathbf{z^s_{t+1}}), \\ & \pi(x^j_t, x^o_t) - \kappa + \beta \mathbb{E}_0 V(\mathbf{x_{t+1}}, \mathbf{z^g_{t+1}}, \mathbf{z^s_{t+1}}), \\ & \pi(x^i_t, x^j_t, x^o_t) + \beta \mathbb{E}_0 V(\mathbf{x_{t+1}}, \mathbf{z^g_{t+1}}, \mathbf{z^s_{t+1}}) \Big\} \end{aligned} \tag{10}$$

where $\mathbb{E}_0$ is the mathematical expectation operator, and $\mathbf{x}$, $\mathbf{z^g}$, and $\mathbf{z^s}$ are the vector of the fish stock, stochastic variations in the fish growth, and the negative shock, respectively. The term κ is the transaction cost of creating or rotating the reserve.

2.3 Simulation

The problem above is numerically solved by approximating the value function with the collocation method.[4] Thus, $V(\mathbf{x}, \mathbf{z^g}, \mathbf{z^s}) \approx \sum_{l=1}^{L} k_l \phi_l$, where ϕ is a degree L polynomial basis function with coefficients k. Thus,

$$\begin{aligned} V(\mathbf{x}, \mathbf{z^g}, \mathbf{z^s}) \approx \max_y \Big\{ & \pi(x^i, x^j) + \beta \sum_{l=1}^{L} \sum_{m=1}^{M} \sum_{q=1}^{Q} w^g_m w^s_q k_l \phi_l(\mathbf{x}, \mathbf{z}^g_m, \mathbf{z}^s_q), \\ & \pi(x^i, x^o) - \kappa + \beta \sum_{l}^{L} \sum_{m}^{M} \sum_{q}^{Q} w^g_m w^s_q k_l \phi_l(\mathbf{x}, \mathbf{z}^g_j, \mathbf{z}^s_q), \\ & \pi(x^j, x^o) - \kappa + \beta \sum_{l}^{L} \sum_{m}^{M} \sum_{q}^{Q} w^g_m w^s_q k_l \phi_l(\mathbf{x}, \mathbf{z}^g_j, \mathbf{z}^s_q), \\ & \pi(x^i, x^j, x^o) + \beta \sum_{l}^{L} \sum_{m}^{M} \sum_{q}^{Q} w^g_m w^s_q k_l \phi_l(\mathbf{x}, \mathbf{z}^g_j, \mathbf{z}^s_q) \Big\} \end{aligned} \tag{11}$$

where w^g_m and w^s_q are the probabilities of the realisation of each state in the growth uncertainty and the negative shock, respectively. The growth uncertainty z^g is discretised with 10 grids ($m = 10$) and the negative shock z^s is with two grids ($Q = 2$). This paper uses the 5 degree Chebyshev polynomials as the basis function ($L = 5$). The coefficients are updated by the Newton method until the convergence criterion is satisfied.

The biological parameters are set to $r = 0.3$, and $m = 0.35$ and the economic parameters

[4] See Judd (1998) and Miranda and Fackler (2002) for the technical details.

are $\bar{p} = 1$, $\bar{c} = 1$, $\delta = 1.5$, and $\theta = 0.2$, and the time discounting rate is 10 per cent. The parameter in the growth uncertainty $\epsilon = 0.1$, and the arriving rate of the negative shock $\tau = 0.01$ and the proportional size of the shock $\alpha = 0.3$.

3 Numerical results

3.1 Fully integrated dispersal process

Figure 1 illustrates the frequency of the switching and shock occurrence under the fully integrated dispersal process. Different transaction costs of switching, from $\kappa = 0$ to $\kappa = 0.035$, are applied. The arriving rate of the negative shock is around 1 per cent. Since the larger is the transaction cost, then the less is the return from switching the reserve, the optimal proportion of the switching period decreases. When the transaction cost is high ($\kappa = 0.05$), one area is closed for the whole period. On the other hand, when the transaction cost is nil, the reserve is switched to a new site in almost every period. An interesting case is that, after a certain level of the transaction cost, the proportions of the switching period and the shock occurrence are corresponding. This implies that the timing of the switching and the shock occurrence are also corresponding. As the shock arrives, the return from continuing to fish at the current fishing grounds falls down with the level of population density. Hence, with the switching strategy, to maintain the harvest and the biomass, the reserve is switched following the shock.

[**Figure 1 about here**]

The density distributions of the biomass, harvest, and net profit are, respectively, presented in Figure 2 for three management scenarios; marine reserve switching, fixed reserve, and no-reserve. In the fixed reserve case, the reserve is permanently fixed at single site, and, in the no-reserve case, the reserve is not created at all times. Compared to the no-reserve case, the other two scenarios with reserves provide a smaller harvest, but higher biomass and net profit. The higher net profit in the management with reserves is due to the stock effect, in which the higher biomass generates less fishing costs. Hence, while the harvest is greater in the no-reserve case, the net profit becomes less due to the stock effect; i.e., fish stocks are overexploited in the management without reserves. Also notice that, compared to the no-reserve case, the management with reserves have smaller variance, especially in the harvest and net profit.

Comparing the marine reserve switching and the fixed reserve strategies, the biomass is likely to become higher in the fixed reserve case, while the harvest and the net profit are greater in the switching strategy. In the switching strategy, the fishing grounds are shifted to more stock abundant areas over time. Consequently, the switching strategy generates the greater harvest and net profit than the fixed reserve case, but it results in smaller biomass. The variances in the biomass, harvest, and net profit between these two managements are similar under the fully integrated process.

[**Figure 2 about here**]

3.2 Sink-source dispersal process

Figure 3 shows the frequency of the switching and shock occurrence under the sink-source dispersal process. In this case, even if the transaction cost is nil, the optimal proportion of the switching period is about a half, but recall that it was close to one in the previous case (Figure 1). Under the fully integrated process, the fish dispersal pattern between each site is homogeneous. Hence, the relative benefit of the spillover effect by closing a fishing area is constant over space. By contrast, under the sink-source process, since the fish dispersal is unidirectional, relatively higher biomass in the source can provide positive spillover to the sink, while the spillover effect is not generated from the sink to the source. Therefore, under the sink-source process, it is optimal to close the source for a longer period. In other words, under the sink-source process, the reserve is switched less times than under the fully integrated system. Also notice that the frequency of the switching and shock occurrence are corresponding after a certain level of the transaction cost. This result is consistent with Figure 1.

[**Figure 3 about here**]

The density distributions of the biomass, harvest, and net profit under the sink-source dispersal process are illustrated in Figure 4. The comparison between the no-reserve and the other two management scenarios is similar to the one under the fully integrated process. The harvest is greater in the no-reserve case, but the biomass and net profit are higher in the management with reserves due to the stock effect. Comparing the switching and the fixed reserve strategies, the biomass is more likely to become higher in the fixed reserve case than in the switching strategy. The fishing grounds are rotated to more stock abundant areas in the switching strategy. Meanwhile, the comparisons in the harvest and in the net profit are not as clear as that in the biomass. Compared to the fixed reserve case, the switching strategy generates a greater harvest and higher net profit with a higher probability. However, due to the large variance, the switching strategy also generates a smaller harvest and less net profit than the fixed reserve case with a higher probability. The greater variance in the switching strategy is due to the rotation of the non-fishing area between the source and sink.

[**Figure 4 about here**]

3.3 Spatially linear dispersal process

Figure 5 depicts the frequency of the switching and shock occurrence under the spatially linear dispersal process. Similar to the result under the sink-source dispersal process, even if the transaction cost is nil, the optimal frequency of the switching is about 0.67, not close to one. In this case, three sites are located along a line, and two sites at the edges are only connected through the site at the centre. By the "edge effect", the population densities become greater at the outsides than at the the centre (Sanchirico and Wilen, 1999). Hence, a greater positive spillover is generated by closing the edges than closing the centre, and thus the reserve is set at the outsides for a longer period. Also notice that the frequency of the switching and shock occurrence are corresponding after a certain level of the transaction cost. This result is consistent over the different dispersal processes. Therefore, the return from fishing at the current fishing grounds significantly declines following a shock, and, in result, the areas should be closed to recover the biomass.

[**Figure 5 about here**]

The density distributions of the biomass, harvest, and net profit under the spatially linear process are similar to the previous cases (Figure 6). Comparing the management with and without reserves, the harvest is greater in the no-reserve case, but the biomass and net profit are smaller due to the stock effect. The rotation of the non-fishing area over time makes the biomass smaller and makes the variance in the harvest and the variance in the net profit greater in the switching strategy than in the fixed reserve case. Since the fishing grounds are shifted to more profitable sites in the switching strategy, it will generate a higher economic return than the fixed reserve case with a higher probability.

[**Figure 6 about here**]

4 Sensitivity analysis

The difference in the density distributions between various management scenarios depends on the relative size of both biological and economic parameters. This section will test how the different values of the harvest fraction (θ), the transfer coefficient (m), and the stock effect affect the density distributions under different management strategies.

4.1 Harvest fraction (θ)

If the harvested populations are more extracted, the marginal benefit of the positive spillover from the reserve to the harvested populations increases. This is because the greater is the harvest fraction, the larger closed area is necessary to compensate the greater reduction in biomass. Figure 7 shows the effect of a large harvest fraction ($\theta = 0.2$) on the density distributions of the biomass, harvest and net profit. With the greater harvest fraction, the fish stock is overexploited in the management without reserves. Consequently, compared to the management with reserves, all of the variables, biomass, total harvest, and net profit, become significantly lower level in the no-reserve case. Moreover, in the no-reserve case, the economic return is even distributed over the negative domain. Also, as the harvest fraction increases, the distributions of the harvest and the net profit increases in the switching strategy, especially under the sink-source and spatially linear processes.

[**Figure 7 about here**]

(to be written)

[Figure 8 about here]

4.2 Transfer coefficient (m)

The fish transfer is an important factor to determine the benefit of reserves. The positive spillover effect from the reserve to the fishing ground depends on the transfer coefficient, m. The smaller is the transfer coefficient, the less the number of fish that transfer from the reserve to the harvested populations. In result, the economic payoffs from the reserve decreases as the transfer coefficient decreases. To test the effect of the weaker linkage between each site, two different transfer coefficients ($m = 0.1$ and $m = 0$) are applied, and results are illustrated in Figures 9 and 10, respectively. Due to the stock effect, the net profit is still greater in the management with reserves compared to the no-reserve case. However, as the transfer coefficient decreases, the difference between the no-reserve and fixed reserve cases becomes smaller, and the difference between the fixed reserve and switching strategies becomes greater.

[Figure 9 about here]

[Figure 10 about here]

4.3 Stock effect

In the previous results, the higher net profit in the management with reserves compared to the no-reserve case is due to the stock effect, in which the greater biomass generates smaller fishing costs. The sensitivity of the stock effect is tested in Figure 11. Figure 11 shows that, without the stock effect, the net profit as well as the total harvest in the no-reserve case are greater than those in the management with reserves.

[Figure 11 about here]

5 Conclusion

Using a dynamic optimisation framework under uncertainty, this paper analyses a fisheries management strategy, marine reserve switching. The key findings are that the switching strategy will be likely to provide a greater harvest and a higher net profit than the fixed reserve and the no-reserve cases. Meanwhile, the population densities are more likely to be smaller in the switching strategy than in the fixed reserve case, while still higher than in the management without reserves. In the switching strategy, the biomass is conserved in the protected area, but the fishing grounds are rotated to more stock abundant areas to exploit the fish stocks. Moreover, due to the rotation over time, the distributions of the total harvest and net profit become larger in the switching strategy than in the fixed reserve case. The numerical results also show that the distribution depends on the fish dispersal process.

References

Grafton, Q., T. Kompas, and P. Ha. 2006. "The Economic Payoffs from Marine Reserves: Resource Rents in a Stochastic Environment." *Economic Record* 82:469–480.

Grafton, Q., T. Kompas, and V. Schneider. 2005. "The Bioeconomics of Marine Reserves: A Selected Review with Policy Implications." *Journal of Bioeconomics,* 7:161–178.

Guenette, S., T. Lauck, and C. Clark. 1998. "Marine Reserves: from Beverton and Holt to the Present." *Reviews in Fish Biology and Fisheries* 8:251–272.

Hannesson, R. 2002. "The Economics of Marine Reserves." *Natural Resource* Modeling,15:273–290.

—. 1998. "Marine Reserves: What Would They Accomplish?" *Marine Resource Economics* 13:159–170.

Hilborn, R., and C. Walters. 1992. *Quantitative Fisheries Stock Assessment: Choice, Dynamics and Uncertainty*. London: Kluwer Academic Publishers.

Holland, D., and R. Brazee. 1996. "Marine Reserves for Fisheries Management." *Marine Resource Economics,* 11:157–171.

Judd, K. 1998. *Numerical Methods in Economics*. Cambridge: MIT Press.

Miranda, M., and P. Fackler. 2002. *Applied Computational Economics and Finance*. Cambridge: MIT Press.

Pezzey, J., C. Roberts, and B. Urdal. 2000. "A Simple Bioeconomic Model of a Marine Reserve." *Ecological Economics,* 33:77–91.

Rodwell, L., and C. Roberts. 2004. "Fishing and the Impact of Marine Reserves in a Variable Environment." *Canadian Journal of Fisheries and Aquatic Sciences* 61:2053–2068.

Sanchirico, J., U. Malvadkar, A. Hastings, and J. Wilen. 2006. "When are No-Take Zones an Economically Optimal Fishery Management Strategy." *Ecological Applications* 16:1643–1659.

Sanchirico, J., and J. Wilen. 2001. “A Bioeconomic Model of Marine Reserve Creation.” *Journal of Environmental Economics and Management,* 42:257–276.

—. 1999. “Bioeconomics of Spatial Exploitaion in a Patchy Environment.” *Journal of Environmental Economics and Management,* 37:129–150.

Sumaila, U. 1998. “Protected Marine Reserves as Fisheries Management Tools: A Bioeconomic Analysis.” *Fisheries Research* 37:287–296.

Figure 1: Frequency of switching and shock occurrence under fully integrated process

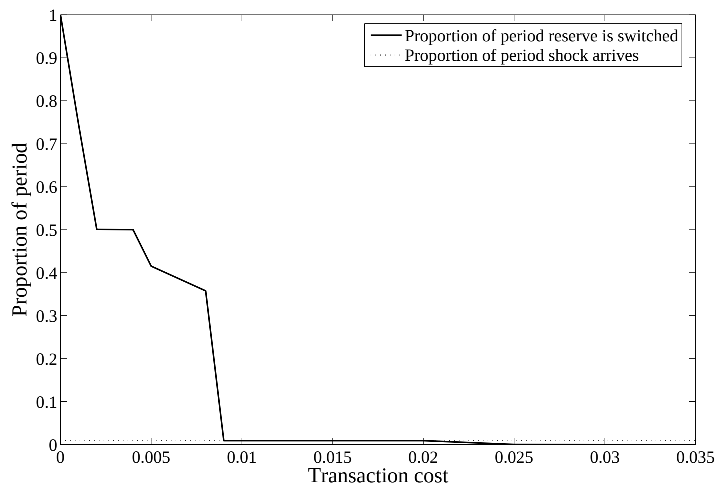


Figure 2: Density distributions of biomass, harvest, and net profit under fully integrated process

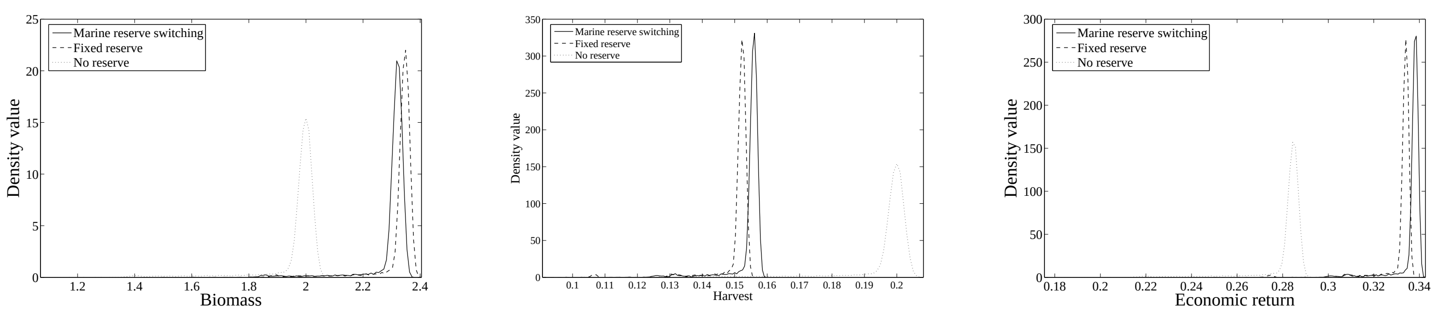


Figure 3: Frequency of switching and shock occurrence under sink-source process

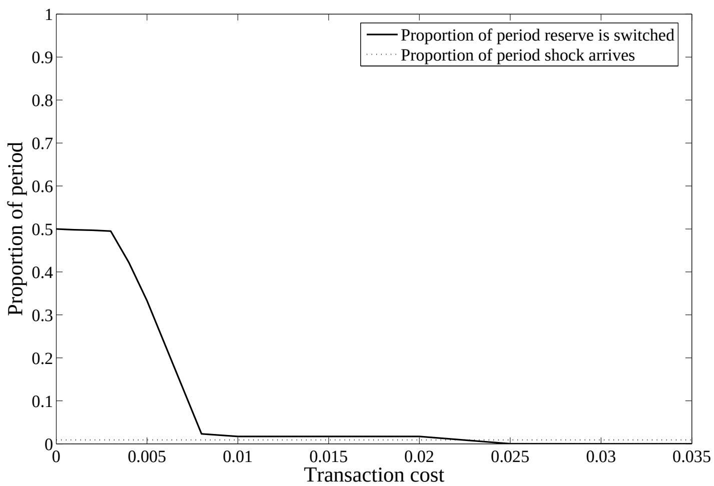


Figure 4: Density distributions of biomass, harvest, and net profit under sink-source process

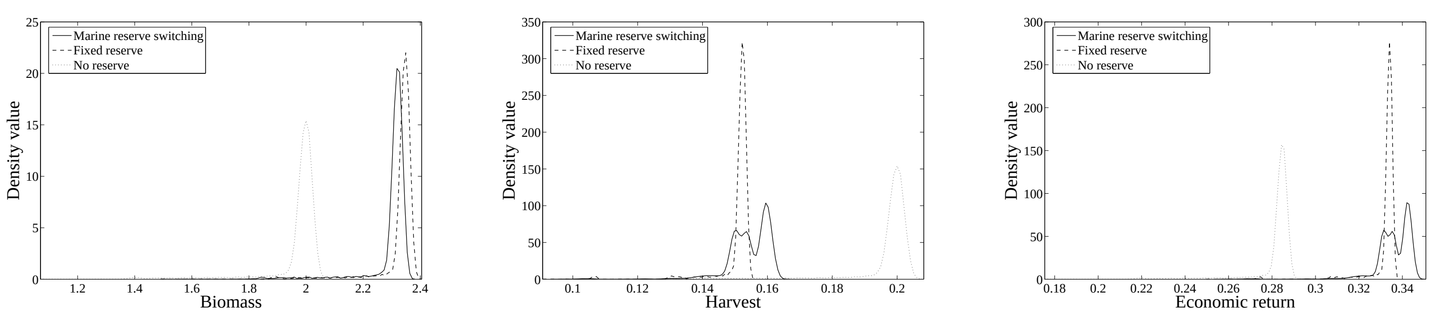


Figure 5: Frequency of switching and shock occurrence under spatially linear process

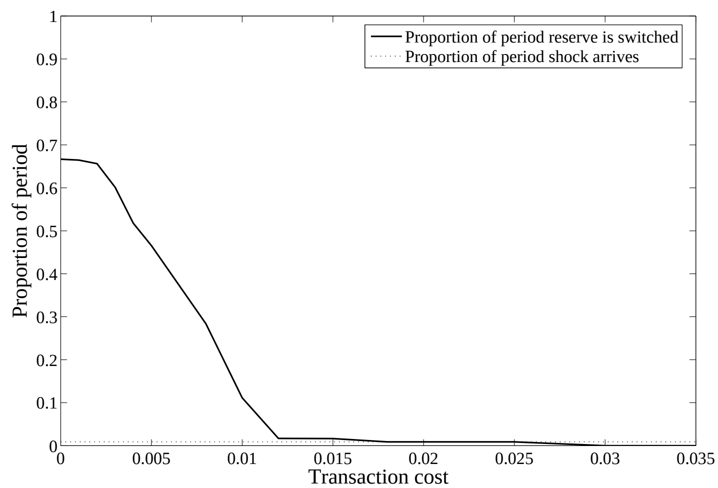


Figure 6: Density distributions of biomass, harvest, and net profit under spatially linear process

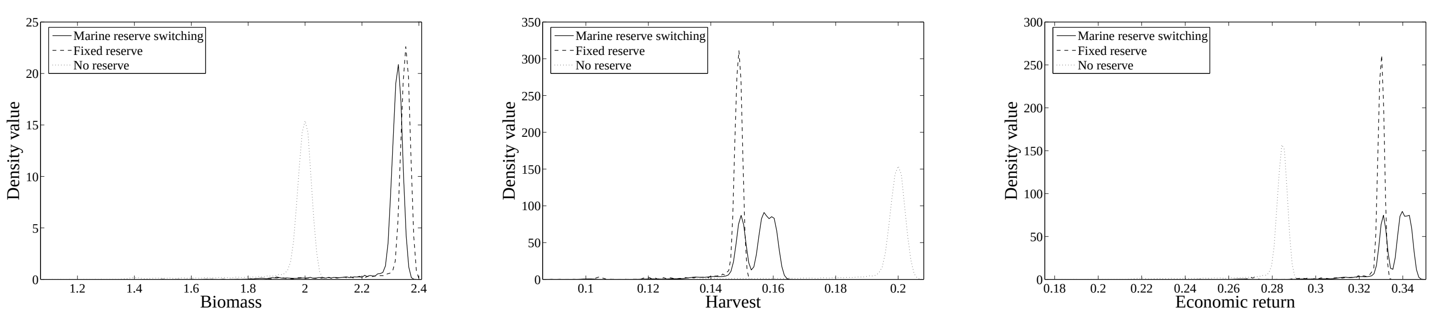
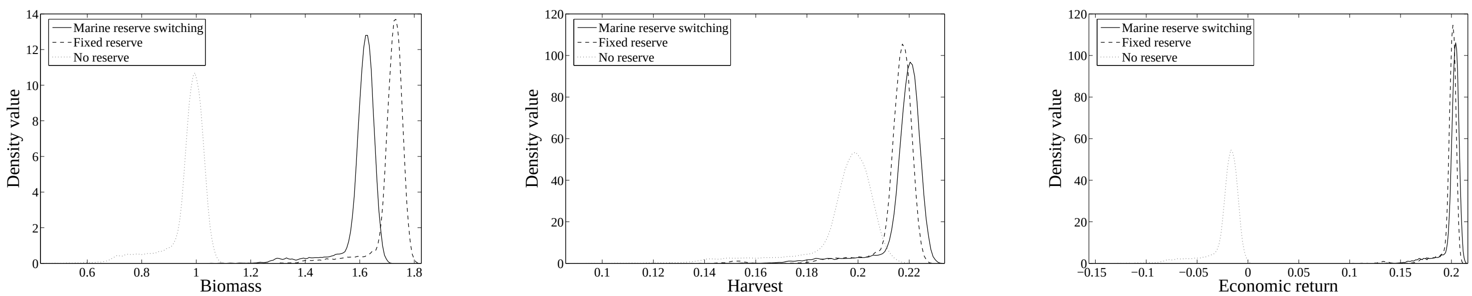
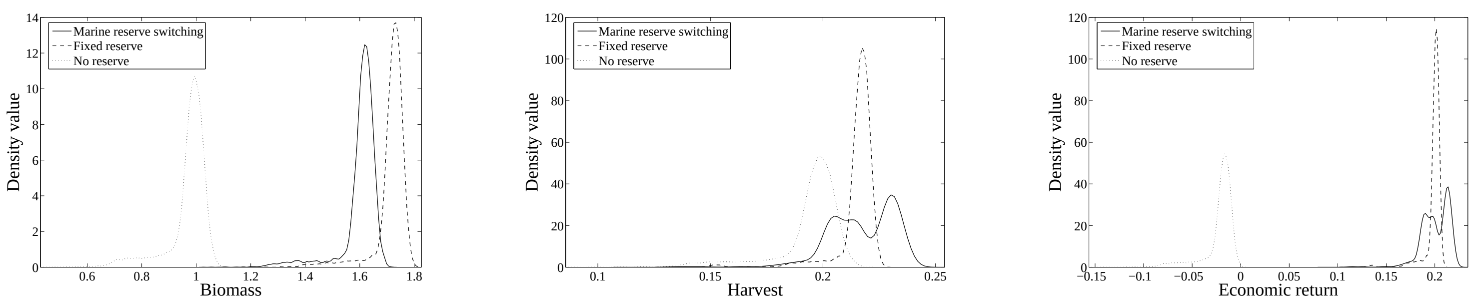


Figure 7: Sensitivity analysis: harvest fraction $\theta = 0.2$

Fully integrated process



Sink-source process



Spatially linear process

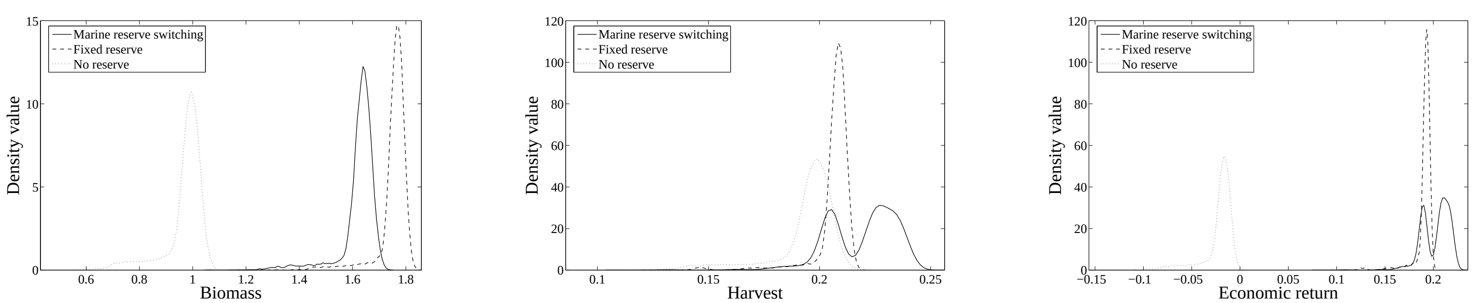
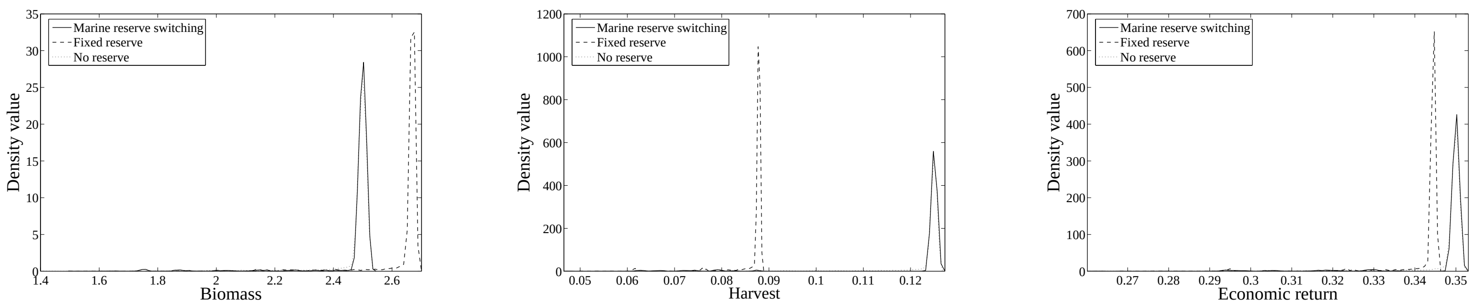
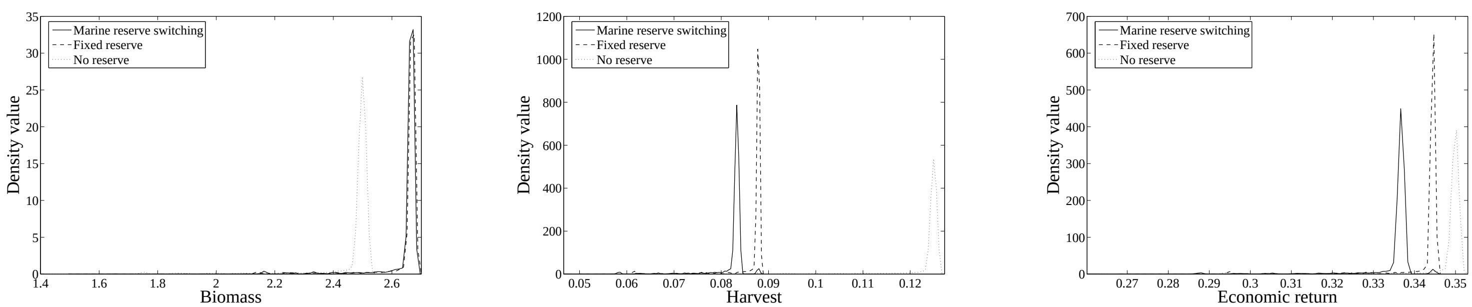


Figure 8: Sensitivity analysis: harvest fraction $\theta = 0.05$

Fully integrated process



Sink-source process



Spatially linear process

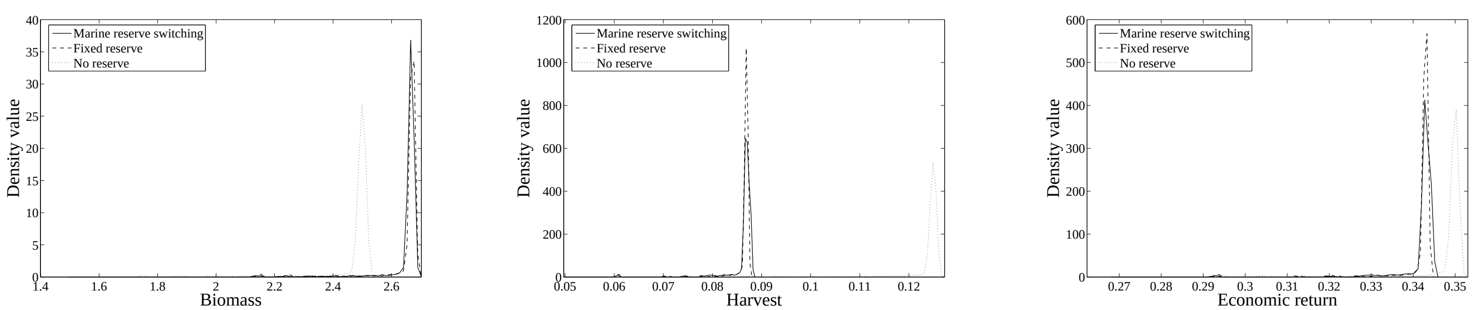


Figure 9: Sensitivity analysis: transfer coefficient $m = 0.1$

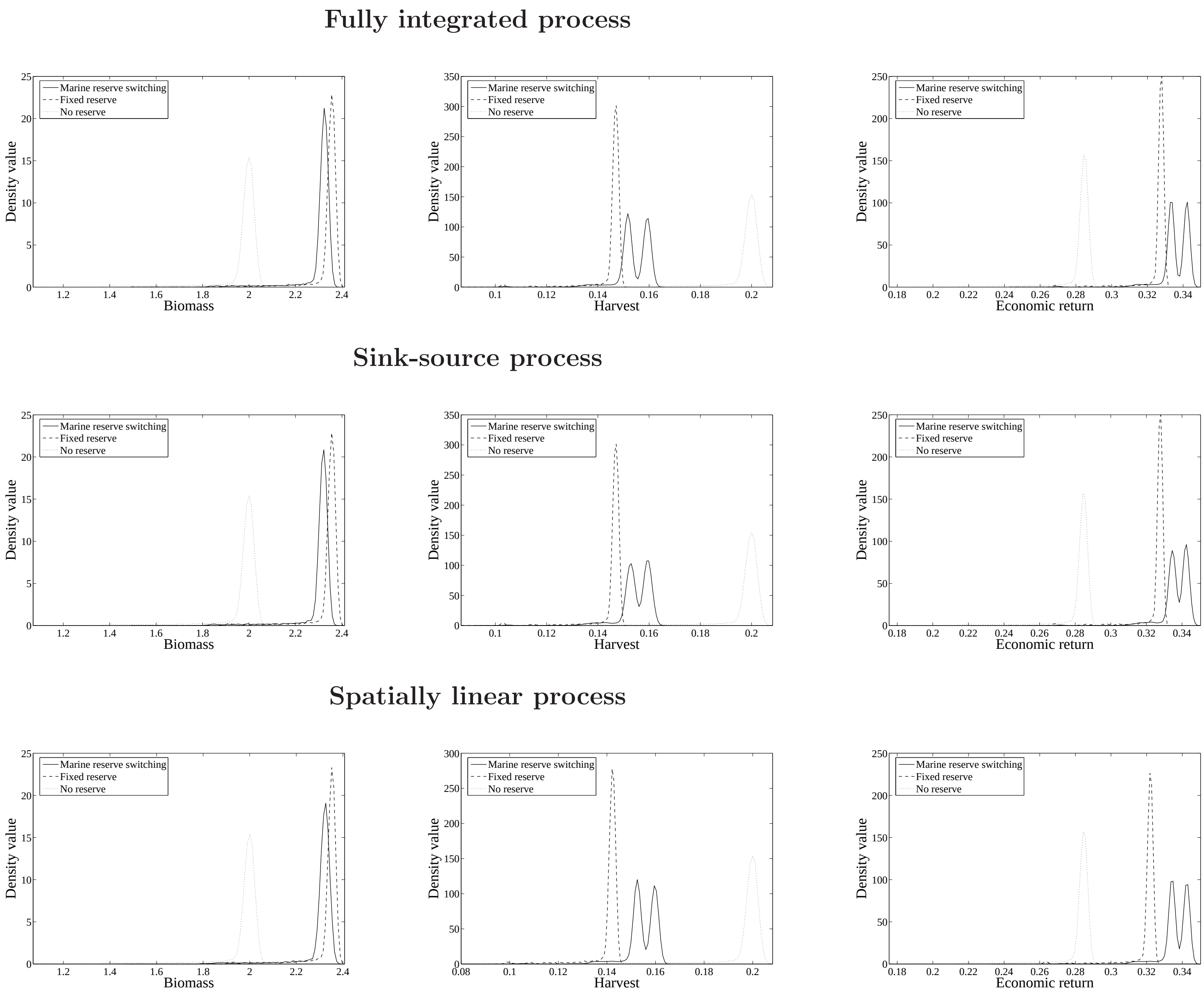
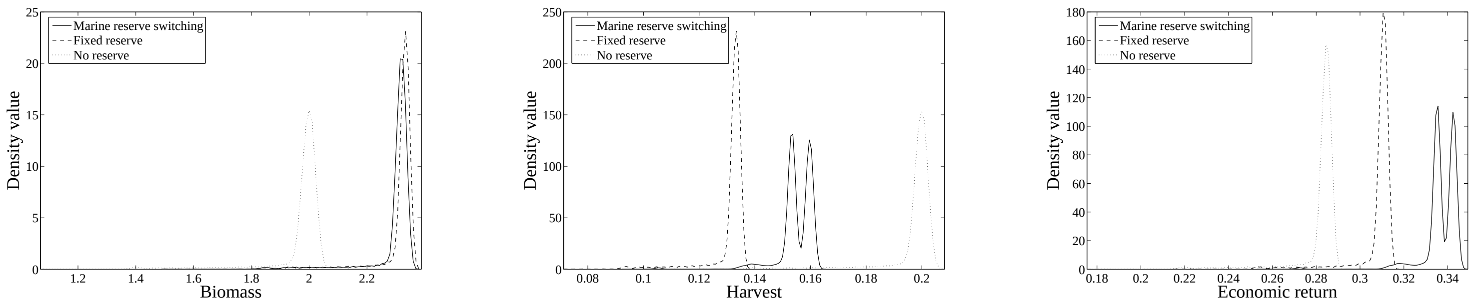
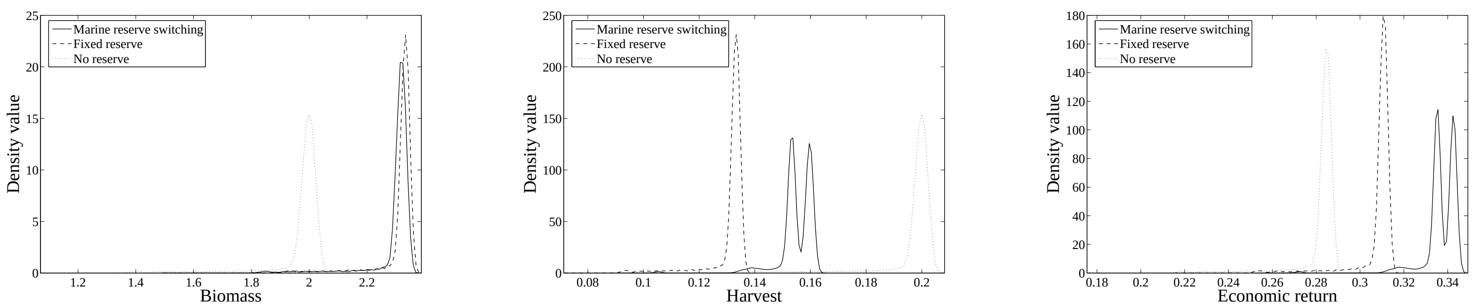


Figure 10: Sensitivity analysis: transfer coefficient $m = 0$

Fully integrated process



Sink-source process



Spatially linear process

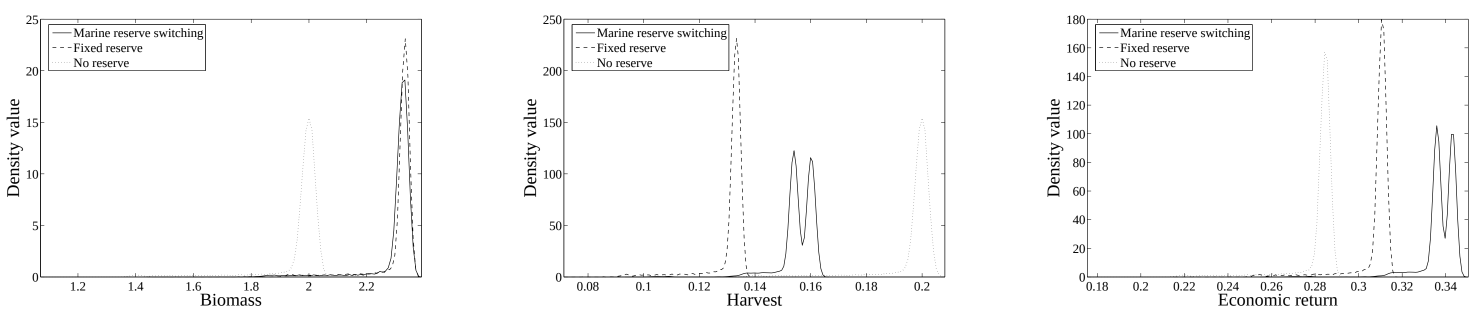
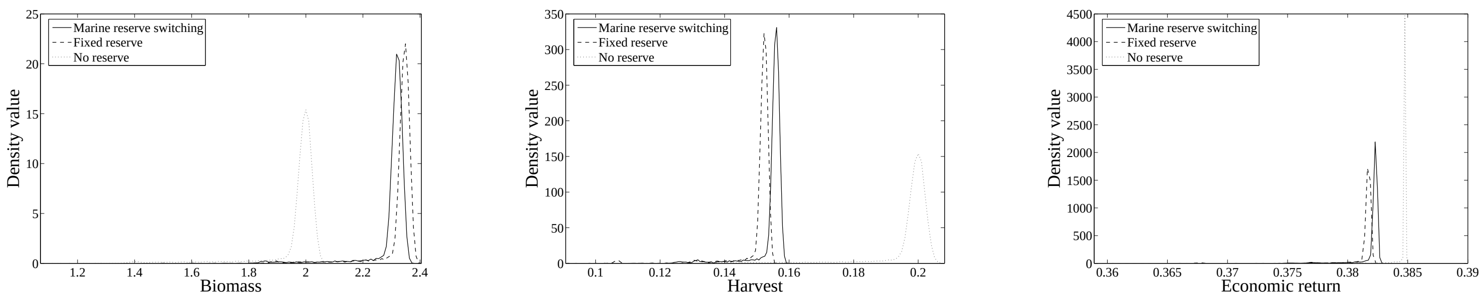


Figure 11: Sensitivity analysis: stock effect

Fully integrated process



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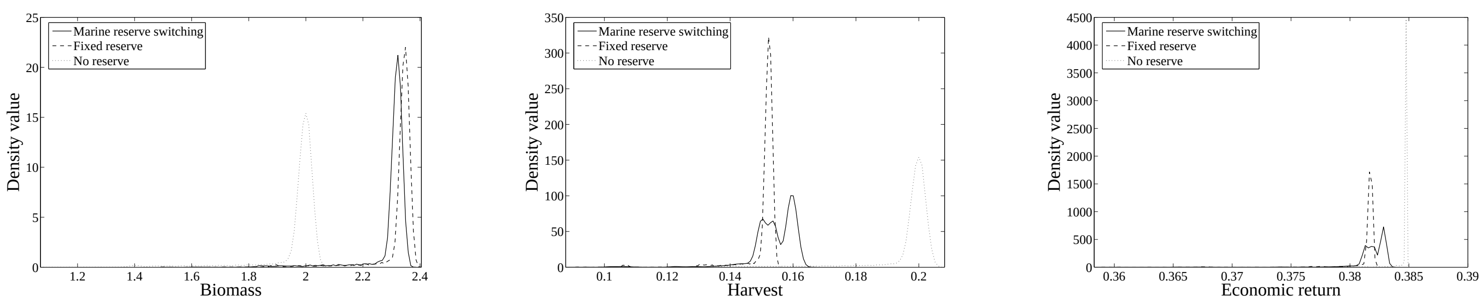

Spatially linear process