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Addendum

Revisiting biological "hot spots" and marine reserve formation

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An article of mine investigating the affect of biological "hot spots" on marine reserve formation (Schnier, 2005) appeared in a recent edition of this journal. Biological "hot spots" are areas within a fishery that possess either a higher carrying capacity or higher intrinsic growth rate than the surrounding regions. The paper initially creates a general theoretical framework that can be utilized to investigate the role of spatial heterogeneity in the resource base. It then parameterizes a distribution of resource heterogeneity to determine the role it plays in marine reserve formation, after which a series of simulations are conducted to determine whether or not the net-present value of the fishery can be increased in the presence of heterogeneity in the resource base.

Although the theoretical model does provide a valid and unique illustration of how the standard optimal control model can be expanded to incorporate spatial heterogeneity in the resource, after the paper went to press I discovered an error within the simulation model. This error, which arises from the parameterized distribution used in the simulation (Eqs. (26) and (30)), generates inaccurate results and conclusions. I offer this addendum both to provide the correct results and to provide some thoughts on the new conclusions.

The errors lie in Eqs. (26) and (30) of the paper, reproduced below.

$$r_{\mathrm{f}}(\xi) = r_{\mathrm{BASE}} + \frac{(r_{\mathrm{MAX}} - r_{\mathrm{BASE}})}{2\alpha_{\varphi}(1-\alpha)}\left[\alpha_{\varphi}^2 - \alpha^2\right] \qquad (26)$$

and

$$K_{\mathrm{f}}(\varphi) = K_{\mathrm{BASE}} + \frac{(K_{\mathrm{MAX}} - K_{\mathrm{BASE}})}{2\alpha_{\Omega}(1-\alpha)}\left[\alpha_{\Omega}^2 - \alpha^2\right]. \qquad (30)$$

These equations result from calculating the integral of the stylized distributions depicted in Figs. 2 and 4 for the respective carrying capacities and intrinsic growth rates of the fishing grounds.[1] A flaw in the integration was recently discovered, leading to the corrected Eqs. (26) and (30):

$$r_{\mathrm{f}}(\xi) = r_{\mathrm{BASE}} + \frac{(r_{\mathrm{MAX}} - r_{\mathrm{BASE}})}{2\alpha_{\varphi}(1-\alpha)}\left[\alpha_{\varphi}^2 + \alpha^2 - 2\alpha\alpha_{\varphi}\right] \qquad \text{(26 corrected)}$$

and

$$K_{\mathrm{f}}(\varphi) = K_{\mathrm{BASE}} + \frac{(K_{\mathrm{MAX}} - K_{\mathrm{BASE}})}{2\alpha_{\Omega}(1-\alpha)}\left[\alpha_{\Omega}^2 + \alpha^2 - 2\alpha\alpha_{\Omega}\right]. \qquad \text{(30 corrected)}$$

The errors caused the intrinsic growth rate or carrying capacity of the fishing grounds to be greater

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[1] Please refer to the original publication for figure references.

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than what it should have been, given the stylized distributions depicted in Figs. 2 and 4. The magnitude of this difference, although small, is sufficient to drive the simulation results to suggest that, in the presence of known spatially heterogeneous growth, there exists a positively sized optimal marine reserve. Under the correctly parameterized distribution, for all cases illustrated within the paper (Tables 1 through 5 and Figs. 3 and 5), the optimal reserve size degenerates to a corner solution and becomes zero. Correcting Eqs. (26) and (30) produces a simulation that supports the results previously illustrated in the literature (Sanchirico and Wilen, 2001; Sanchirico, 2004).

Exploring this alternative reveals that the optimal control model yields solutions which are consistent with those previously discovered by other researchers assuming an open access or limited entry fishery (Sanchirico and Wilen, 2001; Sanchirico, 2004). Closing areas of higher biological value will increase the economic opportunity costs of the closure, rather than generating benefits as found in the paper. Table 1 depicts the opportunity costs of a given marine reserve size using the corrected equations, assuming a few of the heterogeneous population distributions depicted within the paper. Table 1 contains the corrected results, corresponding with the results in Tables 1 through 4 in the paper.

From this table it is apparent that the opportunity costs of a marine reserve actually increase with both the degree of heterogeneity and the maximum carrying capacity or intrinsic growth rate of the fishery. This is somewhat consistent with the simulation results presented in the paper, which illustrated that increasing the maximum intrinsic growth or carrying capacity reduced the optimal size of a marine reserve. This is presumably driven by the fact that areas of higher productive capacity are also more viable as profitable fishing sites and therefore reserving them does not provide sufficient spillover to benefit the fishing grounds via migration. As discussed in the paper, a marine reserve will only benefit the fishery if the spillover from the reserve exceeds the loss in harvest generated from truncating the fishery. This does not occur in the corrected simulation model because the error within Eqs. (26) and (30) allows the carrying capacity and/or intrinsic growth rate to be greater within the fishing grounds than that depicted within the spatial distributions illustrated in Figs. 2 and 4.

The magnitude of the difference between the correct and incorrect equations is relatively small and this suggests that if an external growth benefit existed, which is determined by the distributional parameters of the underlying population, a marine reserve may benefit the population. This may occur in the case of edge effects resulting from a spillover in the habitat quality near the reserve to the surrounding area once that area is protected. However, this would require the derivation of an alternative growth function that is determined by the growth parameters in nearby regions. In addition, as discussed in the paper a biological hot spot could be induced by the creation of a marine reserve. If this is the case, the productive capacity within the reserve would increase relative to a fished state and this may also generate an external growth benefit function. Both of these possibilities may prove to be fruitful research for future endeavors but they are not explicitly accounted for in the paper.

In revising the conclusions drawn from my earlier research, it is evident that, if the resource distribution is known to the managing body, the simulation model yields corner solutions. In fact, if this is the case, the opportunity costs associated with the creation of a

Table 1
Loss in net-present value within the fishery under alternative heterogeneous spatial distributions

Reserve size (α)	2.5%	5%	7.5%	10%	12.5%	15%
Homogeneous						
$r_f = r_R = 0.4$; $K_f = K_R = 100$; $s = 20$	0.10%	0.23%	0.37%	0.55%	0.76%	1.02%
Heterogeneous						
$r_{MAX} = 1.0$; $r_{BASE} = 0.4$; $\alpha_\varphi = 0.3$; $s = 20$	0.13%	0.37%	0.77%	1.33%	2.02%	2.81%
$r_{MAX} = 1.6$; $r_{BASE} = 0.4$; $\alpha_\varphi = 0.3$; $s = 20$	0.19%	0.69%	1.58%	2.78%	4.21%	5.76%
$K_{MAX} = 200$; $K_{BASE} = 100$; $\alpha_\Omega = 0.3$; $s = 20$	0.16%	0.39%	0.71%	1.13%	1.63%	2.22%
$K_{MAX} = 400$; $K_{BASE} = 100$; $\alpha_\Omega = 0.3$; $s = 20$	0.26%	0.80%	1.69%	2.88%	4.27%	5.79%

marine reserve are consistent with earlier research (Sanchirico and Wilen, 2001; Sanchirico, 2004); increasing known heterogeneity increases the opportunity cost of the reserve creation. However, the results from the corrected simulation model suggest that alternative environmental conditions may generate results similar to those reported earlier. I apologize for not finding this error earlier in the research and publication process, but I hope that the theoretical model and motivation for this research will stimulate further research in this area.

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