Marine Reserves: A Closer Look at What They Can Accomplish

Lee G. Anderson, College of Marine Studies, University of Delaware

Abstract. The presents a theoretical analysis of the operation of a commercial fishery in the presence of marine reserves. The sustainable yield and revenue curves for reserves are derived and compared to the analogous curves with no reserves. It is shown that reserves will always reduce the sustainable harvest for any total stock size but in certain, but not all cases, they can provide a positive minimum possible stock size. The effects of different reserve sizes and speeds at which migration takes place on economic and boilogical variables are discussed. It is shown that marine reserves and TACs can both achieve a specific equilibrium biomass level, but they will have different biological and economic effects.

Keywords: Marine reserves, bioeconomics, sustainable yield and revenue curves, dynamic analsysis

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1 INTRODUCTION[1]

The use of marine reserves as a fishery management tool is receiving more and more attention in the literature and in real world management agencies. A National Research Council report recently advocated the use of marine reserves. NRC (1999). Much of the biological literature subsumes the micro-behavior of the fishing fleet in the analysis,[see for example Hastings and Botsford (1999)], but several recent papers have offered a full bioeconomic analysis. See the References for a partial listing.

The purpose of this paper is to provide a summary and extension of the received bioeconomic analysis of focusing on what is known and what can be known using standard models. It will be shown that because of the issues that marine reserves are designed to address, primarily variability and patchiness of the productivity of marine ecosystems and the inherent biological and economic uncertainty in fisheries utilization, that more complicated models and approaches will be necessary in order to increase our understanding of the potential of this management tool.

The analysis draws heavily on Hannesson (1999) which is defined in terms of stock densities. The present model considers density but uses absolute stock size as the state variable. This makes the discussion more transparent and more easily comparable to standard models. The paper extends Hannesson's analysis by deriving sustainable catch and revenue curves which provide a more complete picture of how marine reserves affect the proportion of the stock which is available for harvest, of the ultimate amount of safety that is provided, and of the economic operation of the fleet.

The model is discrete and makes use of some simplifying assumptions, most of which are used by Hannesson, and which are necessary for tractability. To set the stage for the more detailed discussion below, it will prove useful to describe the basic formulation here. It is assumed that fishing takes place during the first part of every period during which there is no growth or migration. After fishing is completed, stock size will grow according to the Schaefer function, and with reserves, fish will migrate between the reserve and the fishable area according to the relative stock density in the two areas. Further, it is assumed that migration and growth are independent.

These are important assumptions because there obviously are interactions between harvest, growth, and migration. However, taking them into account would significantly increase the complexity of the equations without adding much to the general nature of the results. Even with these assumptions, there are no simple analytical solutions for equilibrium stock and fleet sizes. However, solutions can be obtained using a simulation model[2] which serves the dual purpose of describing intertemporal changes as a fishery adjusts to a marine reserve policy. Although the exact time paths for critical variables depend upon the relative sizes of the biological and economic parameters, analysis of the time paths for different reserve sizes and different migration rates can be as revealing as comparing equilibrium values.

[1] This is a condensed version of a paper that will be submitted for puplication, copies of which are available from the author.

[2] The simulation is a standard Smith model, where vessels enter and exit the fleet at rate proportional to the level of profits, adapted to handle marine reserves, with and without TACs, using the equations listed below. Because one of the attributes of marine reserves is the ability to keep the stock above a predetermined level, simulations which can trace the operation of the fishery through time are very useful when analyzing them. Copies of the model, which is constructed using EXCEL, are available from the author.

Because it will be necessary to track total stock size as well as stock size in the two areas, the following notation will be used.

X = total stock size at the beginning of each period.
X_g = total stock size after fishing.
X_o = stock size in the fishable area at the beginning of each period.
X_{og} = stock size in the fishable area after fishing.
X_m = stock size in the reserve at the beginning of each period.

Because there is no fishing in the reserve, there is no need to consider an X_{mg}.

2 BASIC ANALYSIS

Assume a stock of fish which occupies a homogeneous area of constant depth of size A km^2 and that the stock distributes itself uniformly over the area. Assume an instantaneous harvest function

$$y = (q/A)NX \qquad (1)$$

where y is harvest in units of biomass, N is the number of standardized boats, q is the product of the area swept per boat (km^2) and the proportion of biomass encountered which are captured, and X is stock size in units of biomass at the beginning of the period. The quotient q/A is equivalent to the normalized catchability coefficient. Because (1) is the instantaneous decrease in stock size during fishing, total periodic catch is:

$$Y = X[1-e^{-(q/A)Nt_f}] \qquad (2)$$

where t_f represents the length of time fishing takes place. For simplicity, t_f will be assumed to equal 1.

Let the productive capacity of the area be such that each square kilometer can support α units of biomass. The carrying capacity of the area measured in units of biomass, call it K, will therefore equal αA. Assume the periodic growth of the stock after fishing is described by the Schaefer function

$$G(X_g) = rX_g(1-X_g/K) \qquad (3)$$

where r is the intrinsic growth rate and the other terms have already been defined.

Let m (a policy variable) represent the proportion of the area that is set aside as a marine reserve, which means that (1-m) will be the fishable area. The range for m will be $0 \leq m < 1$. When m equals zero, there is no reserve and this provides the status quo reference case. The carrying capacity of the two areas is proportional to their size and so the growth functions of the reserve and fishable area, respectively can be represented as:

$$G_m(X_m) = rX_m[1-X_m/mK] \qquad (4)$$
$$G_o(X_{og}) = rX_{og}[1-X_{og}/(1-m)K] \qquad (5)$$

Equation (4) is undefined and equation (5) collapses to equation (1) when m equals zero. Note that $G_m(X_m) + G_o(X_{og}) \leq G(X_m + X_{og})$. Therefore with a Schaefer growth function, reserves cannot produce increased growth by splitting the stock into separate parts. See below.

It is important to consider the dispersal of fish within the total area in order to capture all of the nuances of marine reserves. Following Hannesson, but stating things in terms of biomass rather than density, a dispersal relationship which will achieve a uniform stock distribution can be expressed by writing the equation for *instantaneous* net migration from the reserve to the fishable area as

$$\underline{M}(X_{og}, X_m, m, z)=z[(1-m)X_m - mX_{og}] \qquad (6)$$

where z is the fraction of the stock that will be moving at any instant in time. Hannesson's logic is that during migration, zX_{og} units of stock in the fishable area will be moving at any instant and mzX_{og} of it will end up in the reserve. Similarly zX_m units of stock in the reserve will be moving at any instant and $(1-m)zX_m$ of it will leave the reserve and end up in the fishable area. Migration over a period of time will be:

$$M(X_{og}, X_m, m, Z)= Z[(1-m)Xm - mX_{og}] \qquad (6a)$$

where $Z= (1-e^{-zt})$. As t increases, Z approaches 1 and $M=(1-m)X_m - mX_{og}$ which means that X_{og} approaches

$$X_{og}(\infty) =X_{og}-mX_{og} +(1-m)X_m =(1-m)(X_{og}+X_m)$$

Therefore without fishing or growth, the density in the fishable area becomes

$$(1-m)(X_{og}+X_m)/[(1-m)A]=(X_{og}+X_m)/A$$

Similarly, as t gets large X_m approaches

$$X_m(\infty) =X_m+mX_{og} -(1-m)X_m= m(X_{og}+X_m)$$

The density in the reserve will also equal $(X_{og} +X_m)/A$ and so the stock will approach uniform distribution throughout the area. By a similar line of reasoning if t equals 1, a uniform distribution will be achieved in one period if z equals infinity. For purposes here, migration will be represented by (6a) and it is assumed that t equals the period for which the growth function is defined.[3] Note that (6a) equals zero if m=0, because by definition X_m equals zero.

The total harvest in the fishable area will be analogous to equation (2) except for the change in the area available for fishing.

$$Y_o= Y(X_o, N, m) = X_o(1-e^{-\{q/[(1-m)A]\}Nt_f}) \qquad (2a)$$

[3] The length of time available for migration is important, and it is captured in this function. Z can range between 0 and 1, and an increase in Z can be viewed as the result of either an increase in z or the migration time.

This means that for any combination of X_o and N, harvest will increase with m, because the available stock will be congregated in a smaller area.

The long run periodic profit function for an individual boat will be

$$\pi = P\,Y_o(X_o, N, m)/N - C \qquad (7)$$

where P is price of output, and C is the sum of fixed and variable costs. There will be an economic equilibrium when (7) equals zero, or when.

$$Y(X_o, N, m)/N = C/P \qquad (7a)$$

Because of the density dependent characteristic of the harvest function, it follows that for a given N, as m increases, this condition will hold at a lower absolute stock size. In some sense, therefore, a mitigating factor of marine reserves is that the fleet can maintain itself at lower absolute levels of available stock size.

With marine reserves in place, the change in stock size in the two areas can be represented as

$$X_o(t+1)-X_o(t)=G_o(X_{og}(t))+M(X_{og}(t),X_m(t),m,Z) - Y_o(X_o(t),N,m) \qquad (8)$$

$$X_m(t+1)-X_m(t)=G_m(X_m(t))-M(X_{og}(t),X_m(t),m,Z) \qquad (9)$$

where X_{og} = X_o-Y_o(X_o, N, m). There will be a biological equilibrium when (8) and (9) equal zero simultaneously. Catch, a function of X_o, must equal the sum of the growth in the fishable area plus the migration to the fishable area, both of which are functions of X_{og}. Also growth in the reserve, a function of X_m, must equal migration from the reserve, which is a function of X_m and X_{og}. When m equals zero, equation (9) is undefined and equation (8) collapses to

$$X(t+1) - X(t) = Y(X(t), N) + G(X_g) \qquad (8')$$

Using (9) it is possible to solve for the equilibrium level of X_m for any level of X_{og}, although certain conditions must be met to insure that the solution is positive. These conditions are important in describing certain aspects of the use of marine reserves. See appendix and the following discussion. Call this stock size the equilibrium correspondence level of X_m, and let it be represented by

$$X_m' = X_m'(X_{og}, m, Z) \qquad (10)$$

Equation (10) is undefined when m = 0.

Since X_m is a function of X_{og} which is equal to X_o-Y, there will be three independent unknowns with a reserve policy: X_o, Y, and N. The equilibrium values of these variables can be obtained using the three equations formed by substituting (10) into (9) and then setting equations (7), (8), and (9) equal to zero. The time subscripts have been subsummed.

$$Py_o(X_o, N, m) - NC=0 \qquad (7a)$$

$$Y_o(X_o, N, m) = G_o(X_{og}) + M(X_{og}, X_m', m, Z) \qquad (8a)$$

$$G_m(X_m') = M(X_{og}, X_m', m, Z) \qquad (9a)$$

For any m, let the solution values be $X^*_o(m)$, $Y^*(m)$, and $N^*(m)$. The equilibrium values of X_{og}, X_m, and X can be obtained using these solution values.

When m = 0, there are only two unknowns, X and N. These equilibrium values can be obtained using equations (7a) and (8a). In this case, the stock in the fishable area, X_o, is the total stock, X, there is no migration, catch is equal to growth, vessel profits are zero, and fleet size is such that it will harvest the annual growth.

3 SUSTAINABLE YIELD AND REVENUE CURVES

3.1 Basics

An interesting way to analyze reserves is to compare the curves which are analogous to the status quo sustainable yield and sustainable revenue curves. This will be done for various combinations of Z and m using a specific case where A= 10,000, α = 1, r =.3, q = 3, and P =25. For comparison purposes, two levels of C, 20 and 40, will be used.

With no reserves, the relationship between sustainable yield and total initial stock size follows from equation (8a) where the migration term is equal to zero. In the discrete model, this is somewhat more complex because catch is a function of X but growth is a function of X_g. This can be addressed by noting the relationship between any X_g and the potential fishable stock the next period.

$$X(X_g)= X_g + G(X_g) \qquad (10)$$

The range of X_g is between 0 and K. X_g will be zero if the entire stock is harvested and it will equal K if there is a virgin biomass and there is no fishing. At both of these extremes, G(X_g) equals zero. Therefore X(0) = 0 and X(K) =K. The sustainable yield as a function of total initial stock size can be drawn by plotting G(X_g) against X_g+G(X_g). The sustainable yield from a fishable stock size of X_g + G(X_g) is G(X_g) because if G(X_g) is harvested, the growth from the stock after fishing will be G(X_g). For purposes of constructing the sustainable revenue curve, the fleet necessary to harvest these yields given the corresponding initial stock sizes can be calculated as follows.

$$N=(A/q)\ln[X_o/(X_o-Y)] \qquad (11)$$

In order to produce a sustainable yield curve with reserves that is analogous to the status quo curve, sustainable yield must be plotted against total stock in the entire area. This can be done because there is a unique equilibrium total stock size for every level of X_{og}, the stock size in the fishable area after fishing. This relationship, which is the more generalized form of (10), can be expressed as follows.

$$X(X_{og})=X_{og}+G_o(X_{og})+M[X_{og},X_m'(X_{og},m,Z),m,Z] + X_m'(X_{og},m,Z) \qquad (10a)$$

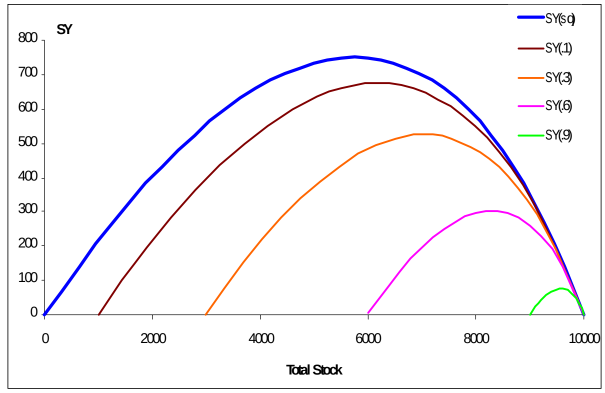
The difference is that for every level of X_{og}, the equilibrium correspondence level of X_m and the equilibrium migration to the fishable area are included. The first three terms are the fishable biomass and the fourth term is the biomass in the reserve. The sustainable yield in a reserve is the sum of the growth of the fishable stock and migration into the fishable area, and the equivalent sustainable yield function can be obtained by plotting $G_o(X_{og}) + M[X_{og}, X_m'(X_{og}, m), m, Z]$ against $X(X_{og})$ as X_{og} varies over the relevant range from 0 to (1-m)K. The fleet size necessary to harvest these sustainable catch levels can be calculated by the equivalent form of (11) where A is multiplied by (1-m).

This is a sustainable yield and therefore it is necessary to talk in terms of the *equilibrium* total initial stock size. There are an infinite number of combinations of X_{og} and X_m that will equal any level of X. The above equation only considers a given level of X_{og}, its equilibrium correspondence level of X_m, and the resultant growth and migration.

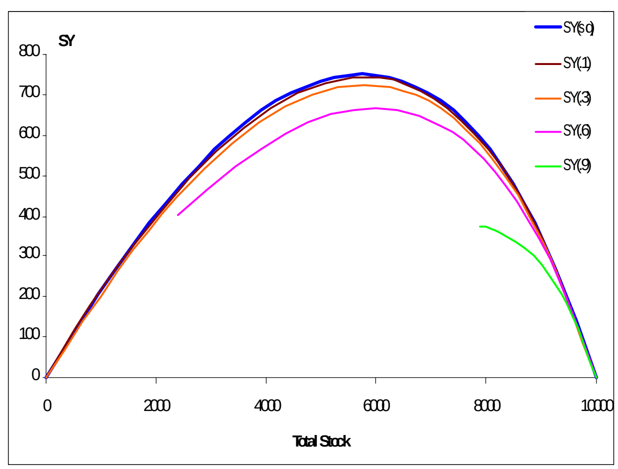
The range of possible equilibrium levels of total X is crucial to the analysis because with reserves the minimum equilibrium biomass can be greater than zero. In fact, one explicit purpose of marine reserves is to accomplish just that. As shown in the appendix, whether this will occur or not, depends upon the relative size of Z and r. If $Z \leq r$, the minimum possible biomass will be positive for all reserve sizes. However, if $Z > r$, m must be greater than 1-r/Z in order for the minimum possible biomass to be positive.

3.1 Biological Analysis The notion of a minimum positive biomass and other biological implications of marine reserves, assuming that the Schaefer function captures the essential population dynamics, can be described by examining the reserve sustainable yield curve for different reserve sizes and different migration rates and comparing them to the status quo curve. Consider first the four sustainable yield curves juxtaposed against the status quo curve in Figure 1. They represent reserves of .1, .3, .6, and .9 respectively when Z = 0. This is the extreme case where there is no mixing, but it a useful way to start the discussion. For example, setting a marine reserve equal to 60% of the area means that, when the system reaches an equilibrium, 6,000 units of biomass are forever protected from exploitation. The relevant range for exploitation purposes is from 6,000 to 10,000. Over that range, the stock size in the fishable area varies for 0 to 4,000. The sustainable harvest is the growth can be generated over that range. A comparison of the set of curves shows that in all cases, the potential sustainable harvest from any given total stock size is reduced for any marine reserve, and the larger the reserve size, the larger is the reduction. In addition, in this case where Z < r, the minimum possible total equilibrium stock is positive for all m and it increases with m.

Consider now the sustainable yield curves for the case where Z equals .5 in Figure 2. Compared to the previous case, the sustainable yields are higher for each equilibrium total stock size although they are still less than the status quo level. Note also that for low levels of m, the reserve curves become



almost indistinguishable from the status quo curve. As Z approaches 1, this will be true for all reserve curves. The reason the sustainable yields are higher than in the previous case is that migrating fish from the reserve are available for harvest; it is composed of the sustainable growth in the fishable area and the sustainable migration from the reserve. However, this extra harvest comes at the expense of reduced protection to the stock in the reserve. The minimum possible stock size is reduced for every reserve size. And since Z (.5) is greater than r (.3), m must be greater than .4, (1-.3/.5), in order for the minimum possible stock size to be positive. The reserve sustainable yield curve for m equals .1 and .3 intersect the origin.



Note that the lowest possible stock size when m = .6 is no longer 60% of the carrying capacity. The lowest possible stock size in the reserve is the equilibrium correspondencelevel of X_m when X_{og} is equal to zero. Using equation (A3), this is equal to 2000 is this case. Using equation (4), the growth rate in the reserve at this stock size equals 399. The interpretation of this extreme point on the reserve sustainable yield curve is as follows. If every last fish in the fishable area is harvested every period, eventually an equilibrium will be reached where the stock size in the reserve equals 2000 and growth in the reserve equals 399. With a end of period stock size in the fishable area equal to 0 and a reserve stock size of 2000, migration to the fishable area will also equal 399. Since the amount leaving the reserve is equal to growth, the stock size in the reserve will remain constant. The 399 units which migrate can be taken in perpetuity and harvests consists exclusively of migration.

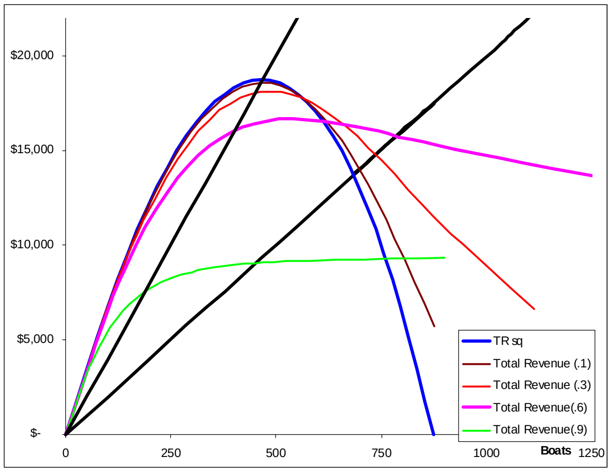
The other points on the reserve sustainable yield curve are generated by letting X_{og} increase from 0 to (1-m)K. If X_{og} is maintained at a fixed level, eventually an equilibrium will be reached where the stock size in the reserve is such that the migration from the reserve and the growth in the fishable area is just equal to the catch necessary to maintain X_{og}. As X_{og} increases, the equilibrium total stock size increases and the sustainable yield will be the sum of growth in the fishable area and migration to the fishable area which is equal to growth in the reserve.

The biological effects of marine reserves can be summarized as follows. Marine reserves can not increase sustainable yield for a given total stock size, although they can potentially provide for a minimum possible stock size. Reserves can have no possible benefit to commercial exploitation unless there is migration to the fishable area. Ironically, however, while high migration levels do allow for more harvest benefits they reduce and in some cases, eliminate the absolute amount of stock safety provided.

3.2 Economic Analysis To see the effects of reserves, note how they will affect the fishing behavior. The long run implications can be noted by observing how reserves change the sustainable revenue curves. This is demonstrated in Figure 3. The sustainable revenue curves are derived from the equivalent sustainable yield curves in Figure 2. The total cost curves for the two cost levels are also pictured. The "high" cost curve intersects the curve in the positively sloped portion of the curve while the "low" cost curve intersects it in the downward slopped portion. When Z is equal to 0, the sustainable revenue curves for reserves lie completely within the status quo revenue curve. This is not the case, however, when Z is positive. The sustainable revenue curve can lie outside the status quo curve at higher fleet sizes. When there is a positive minimum stock size, this is because sustainable yield approaches the growth from that stock size as the fleet approaches infinity. See the revenue curve for m = .9. It can also occur because it takes a larger fleet to take the same sustainable catch at the lower stock sizes. See the revenue curve for m = .6. Although the reserve sustainable yield curve is almost identical to the status quo curve, the reserve sustainable revenue curve is very different from the status quo curve at high fleet sizes.

With the higher cost curve, the intersection of the curves always takes place at a lower fleet size and a lower catch level than with no reserves. With the lower cost curve, however, it is possible that the intersection can take place at a higher fleet size and a higher catch level. Therefore in some cases a reserve can increase equilibrium fleet size and equilibrium catch level. This is merely the result of the intersection of the two curves. There is no inherent increasein biological productivity due to reserves.[4]

It is interesting to note how the equilibrium values of the important biological and economic variables vary with changes in m and Z. The paper from which this discussion is



condensed presents a detailed tabular and graphical analysis of this. One important points is that in some cases the level of Z will have an effect on the size of the variable, and these effects are accentuated in the middle range of m. At high and low levels of m, the differences are small. The main results can be summarized as follows.

Equilibrium fleet size will normally decrease with m, but with low costs and a high Z, it can increase over some ranges. Total equilibrium initial stock size will always increase with m but the relationship is less direct at lower levels of m when Z is relatively high. Total initial stock is comprised of the initial stocks in the two areas. The equilibrium level of X_o always decreases with m but there is little difference with respect to Z. However the equilibrium level of X_m increase with m, and there is a difference with Z, and this increase more than

[4] While a main focus of marine reserves has been the effect on stock, catch, and fleet, it is clear from the curves that the sustainable maximum economic yield will always be decreased with reserves. As m increases, the MEY total stock size increases, the efficient fleet size decreases and the net sustainable profits decrease. The higher the Z the smaller will be the increase in stock size and the lower will be the decrease in fleet size and sustainable profits.

compensates for the decreases in X_o and so total equilibrium initial stock size will increase.

Total sustainable catch is composed of growth in the fishable area and migration. The former decreases monotonically with m and and the level of Z has little effect on this. On the other hand migration will initially increase with m and the increase will be greater with higher Z. Therefore equilibrium harvest will always be higher with higher levels of Z. Equilibrium harvest will always decrease with reserves if the status quo equilibrium is in the upward sloping portion of the revenue curve, but the decrease will be lower with higher levels of Z. Equilibrium harvest can increase for low levels of m if the status quo equilibrium is in the downward sloping portion, and these increases will be greater for higher levels of Z. These increases are possible because even though sustainable yield will decrease for every total stock size with reserves, the higher equilibrium total stock size in this range may have a higher sustainable yield on the marine reserve sustainable yield curve.

Also as m increases the percentage of harvest that comes from migration increases and this percentage increases with Z. Further the equilibrium stock density in the fishable areas increases with m and this density increases with Z. While the equilibrium stock size in the reserve will decrease, it takes a higher stock density for the fleet to break even as the reserve size is increased.

Another way to consider the economic effects of reserves is to observe the average cost for fish. Recall that with reserves less of the productive capacity of any level of total stock is available for harvest, and the flip side of this is that each level of output will cost more and this cost increase gets larger as m increases. The cost differences are more pronouced in the backward-bending portion of the sustainable average cost curve which corresponds to the foreward-falling portion of the sustainable revenue curve.

4 INTER-PERIOD DYNAMICS

4.1 Basics

In addition to the equilibrium analysis, it is interesting to note how the inter-period dynamics are affected by introducing reserves. Although this will depend upon the relative sizes of the various economic and biological parameters, using the simulation model to derive the phase diagrams of fleet and stock size for various levels of Z and m can be quite revealing. Starting with a virgin biomass and a small fleet reserves tend to reduce the amount of "overshoot" on the path to the equilibrium and also to make the paths less cyclical. In fact, with relatively high m's and z's the path to the equilibrium decreases monotonically in stock and increases monotonicall in fleet size.

Perhaps the phase diagrams which start at the status bioequilibrium are more revealing for policy purposes. The most notable thing is that even when the ultimate result is an increase in fleet size, initially it will fall. And when there is a decrease in fleet size, there is never a monotonic decrease. Along the path, the fleet will get lower than it has to. Marine reserves will be a hard sell to the industry.

4.2 Safe Minimum Biomass Levels One of the proposed advantages of reserves is their ability to achieve a specified safe minimum biomass level, (SMBL). See especially Lauck et. al. (1998) which discusses the possibility of using marine reserves to hedge management bets in a world of uncertainty. While they warn against the dangers of developing a general model of reserves given the variety of ecological systems and management regimes (page S76), it will be useful to interpret the results of this model in that context. Their model is analogous to the one is this paper except that they use a different biological function. They also assume the fishery is controlled by a TAC policy but they do not consider the micro-behavior of firms.

To begin this discussion, note that a marine reserve policy can cause the equilibrium biomass to occur at any specified level by selecting the appropriate m. For example, given the parameters used above, a SMBL of 0.6 of the carrying capacity (the one used by Lauck et. al.) can be achieved by setting m equal to .73 when Z is equal .5.

For comparison sake, it is interesting that following Homans and Wilen (1997), it is possible to develop a TAC policy that will also achieve any specified SMBL. Further, the TAC policy can be used in the status quo situation and also in combination with a reserve policy. This is accomplished by specifying that the TAC be a function of stock size and selecting the parameters of the function such that it will intersect the relevant sustainable yield curve at the desired SMBL.

In terms of this model, it is necessary to state the TAC function in terms of stock size at the end of the season because this is what determine stock growth.

$$TAC(sq) = \alpha + \beta(X - TAC) \qquad (12)$$

Solving for TAC obtains a relationship between TAC and initial stock size

$$TAC(sq) = [\alpha + \beta X]/[1-\beta] \qquad (12a)$$

Recall from equation (10), that with reserves any total equilibrium stock size is made up of a unique combination of X_o and X_m. Therefore it is possible to set a TAC with reserves based on stock size in the fishable area that will achieve a specified total X by substituting its component X_o

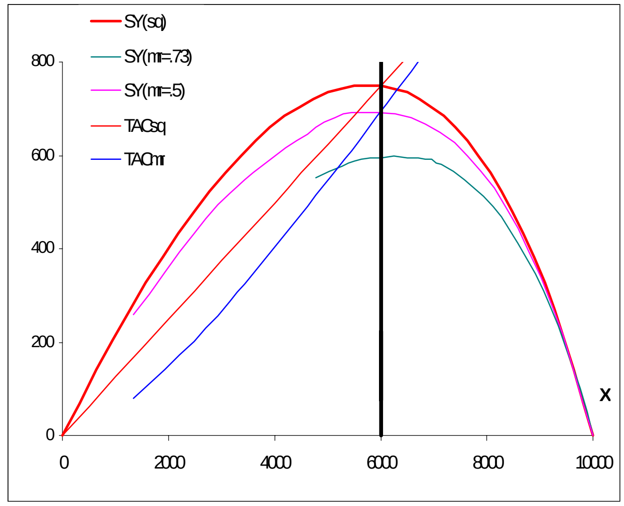
into (12a).

$$TAC(mr) = [\alpha + \beta X_o]/[1-\beta] \quad (12b)$$

It follows that there are three different ways to achieve a stock equilibrium equal to a SMBL; a pure marine reserve policy, a pure TAC policy, and a combined marine reserve/TAC policy. The combined policy will have to use a reserve size that is smaller than the one which will achieve the SMBL independently.

To make the remaining analysis comparable to Luack et. al., the TAC functions will be set such that α is zero which means that the TAC is proportionate $\{\beta/(1-\beta)\}$ to the relevant initial stock size. Let b represent this factor of proportionality. The analysis can be summarized in terms of Figure 4 which pictures the sustainable yield curves for the status quo situation and for a marine reserves with m equal to .5 and .73 respectively. The latter is the reserve size that will achieve the SMBL independently. For now note that the sustainable yields are different at the SMBL on the different curves. In order to achieve the desired SMBL in the status quo situation it is necessary that the status quo TAC line, equation 12a, intersect the status quo sustainable yield curve at 6000. This will occur when b equals .111.

For comparison purposes, consider the combination TAC/MR policy to achieve the SMBL when m equals .5. To make the TAC curves comparable on the graph, equation (12b) must be computed using X_o, but resultant value must be plotted against the equilibrium level of X associated with any given X_o. When b equals .205, this curve will intersect the relevant reserve sustainable yield curve at X equal 6000. See the lower TAC line.[5] The value for b is higher with the reserve since more of the initial stock size can be harvested while maintaining an equilibrium because replenishment is coming from both migration and stock growth. While the equilibrium catch level is less with this combined policy than with a status quo TAC, it is higher that the pure marine reserve policy. This can be summarized in Table 1 which shows combinations of m and b that will achieve the SMBL of 6000 when Z equals .5 as well as the resultant equilibrium levels of X_m, Y, season length and catch per boat.[6] Compare first the first and last columns which represent the pure TAC and the pure marine reserve policies. The difference is that the marine reserve will result in a lower harvest but will provide a



protected stock in the reserve area and will not produce the race for fish which creates an overcaptialized fleet and a shortened season which results in inefficiencies in harvest and processing. With a pure TAC the season length is reduced to .313 of the allowable fishing days and catch per boat is reduced from the open access level of .8 to .58. By combining the two policies, it is possible to get a trade-off between the advantages of each. As m is increased sustainable harvest falls but the inefficiencies are reduced and the size of the protected stock goes up.

m	0	.1	.3	.5	.73
b	.111	.122	.153	..206	na
Y	748	742	725	693	598
N	1420	1406	1347	1234	747
Y/N	0.58	0.53	.54	.56	.8
Season length	0.313	.319	.345	.405	1
Xm	na	660	1985	3322	4959

Table 1 Policies That will Acheive an Equlibrium Biomass of 6000.

[5] As a side light, note that a constant TAC policy, which is represented by a horizontal line, will always produce a lower equilibrium stock size in a marine reserve than it will in the status quo situation.

[6] The simulation model was used to calculate the combinations of m and b necessary to achieve SMBL and to trace the effects on the economic and biological variables.

All three policies pictured in Figures 4 will achieve a deterministic equilibrium stock size of 6000. However, the real issue is how to they will compare with respect to maintaining the SMBL with stochasticity in biological and economic parameters. While it is beyond the scope of this paper to provide a definitive answer, it is possible to consider the issue by performing a Monte Carlo analysis of simulation runs on these specific examples. The results of two such studies are provided in Tables 2 and 3. The variables are the number of times the stock falls below the SMBL, the average annual harvest, and the average annual stock size. The initial conditions were a virgin biomass and a fleet of 20. There were 1000 trials and each trial considered an operation period of 200 years. In the first test, it was assumed that the intrinsic growth rate could vary uniformly between .5 and 1.5 of its deterministic value. The pure status quo TAC policy out- performed the pure MR policy on all counts. The above graphical analysis would lead one to believe that the pure TAC policy would result in a higher average yield, but it also caused the stock size to fall below the SMBL fewer times by a small but statistically significant amount. It also produced a higher average stock size. There is no difference between the SQ/TAC and the MR/TAC except for the expected difference in average catch. However, the last comparison shows that a MR reserve will perform better if it is combined with a TAC to achieve the SMBL.

	SQ/TAC	MR	Significant
Avg. Count	91.97	93.92	yes
Avg. Y	746	597	yes
Avg. X	6111	6089	yes
	SQ/TAC	MR/TAC	Significant
Avg. Count	91.97	91.36	no
Avg. Y	746	693	yes
Avg. X	6111	6109	no
	MR	MR/TAC	Significant
Avg. Count	93.92	91.36	yes
Avg. Y	597	693	yes
Avg. X	6089	6109	yes

Table 2. Comparisons of Policies with Biological Variability.

The very nature of the TAC policy puts a stronger control on harvest, and perhaps that explains the slight superiority of TAC related policies with respect to the number of times the stock falls below the SMBL. To test this, the second study followed the Luack et. al analysis and assumed the actual TAC varied stochastically as well. In the real world, this could result from the inability to accurately measure stock size or to enforce the TAC. It was assumed that the actual TAC varied uniformly between .8 and 1.2 times the calculated amount. As demonstrated in Table 2, there is no difference between the policies with respect to count, but the same differences hold with respect to average harvest and average stock size. The difference between the average stock size is reduced however. These results seem to indicate that as far as achieving a desired stock level a marine reserve is not superior to a traditional TAC policy.

	SQ/TAC	MR	Significant
Avg. Count	93.54	93.75	no
Avg. Y	741	598	yes
Avg. X	6103	6088	yes
	SQ/TAC	MR/TAC	Significant
Avg. Count	93.54	92.79	no
Avg. Y	741	687	yes
Avg. X	6103	6104	no
	MR	MR/TAC	Significant
Avg. Count	93.75	92.79	no
Avg. Y	598	687	yes
Avg. X	6089	6104	yes

Table 3. Comparisons of Policies with Biological and Economic Variability.

It is interesting to note that these results contradict the conclusion by Luack et. al that "a reserve can simultaneously lead to stock protection and a higher level of catch" (page S77). They compare a MR/TAC case where m is .7 and b is .5 and point out that it will produce a average catch that is 1.5 times higher than that of a status quo TAC with a b of .1. While they are correct both of those cases meet their criteria for stock protection (the stock remains above the SMBL *at least* 95% of the time), the straight TAC will cause the stock to fall below the SMBL fewer times than the combined policy. In terms of Figure 8, they are comparing a status quo TAC line that will intersect the status quo sustainable yield curve to the right of 6000. It will indeed produce a lower catch but the deterministic equilibrium stock size will be higher. And given that both cases are subject to the same types of stochaisticity, the stock size will fluctuate about the higher level and hence will remain above the SMBL a larger per cent of the time. When compared on the basis of an exact protection level (the stock remains above the SMBL *exactly* 95% of the time) the pure TAC policy will produce a higher catch level. To put it another way, they could have found a b that was higher than .1 which would have produced a higher average catch and still achieved the desired protection level.

5 SUMMARY AND SUGGESTIONS FOR FUTURE RESEARCH

The following conclusions follow from the above analysis which assumes a Schaefer growth function and homogeneous productivity throughout the fishing area.

1. With marine reserves the sustainable yield for any total stock size will always be less than or equal to the status quo sustainable yield for that total stock size. The lower the migration rate the lower will be the sustainable yield. Looked at from the other side, the cost of producing any sustainable level of effort will be higher with marine reserves.
2. There will be a positive minimum total stock size if $Z \leq r$, or if $Z > r$, and $m > 1 - r/Z$.
3. If the status quo equilibrium is in the downward sloping portion of the sustainable revenue curve, a marine reserve can increase the sustainable fleet size and sustainable harvest. In the short term marine reserves will always reduce fleet size and harvest level.
4. For any Z, increases in m will increase the equilibrium total stock size and the equilibrium stock size in the reserve.
5. A marine reserve policy can cause the open access equilibrium stock size to equal any specified safe minimum biomass level. The higher the Z, the higher is the m that is necessary to achieve a specified SMBL.
6. Compared to the TAC policy that will achieve a given SMBL, the analogous marine reserve policy will achieve a lower equilibrium harvest level but will not result in the overcapitalized fleet or the shortened fishing season which will cause inefficiency in harvest and processing.
7. Any specified SMBL can be achieved by a combination marine reserve/TAC policy. The higher the m in the combination policy, the greater will be the equilibrium stock size in the reserve area and the lower the economic inefficiency from overcaptialized fleets and shortened seasons, but the lower will be the equilibrium harvest level.

Other than the ability to reduce the economic inefficiencies associated with TAC policies to achieve specified SMBLs or perhaps to increase equilibrium yields in certain cases, marine reserves do not appear to have many advantages when viewed in a deterministic Schaefer model. However, one of the proposed advantages of marine reserves is to allow managers to engage in "bet hedging" strategies given the inherent biological, economic, and behavioral uncertainties involved in fisheries management. Unfortunately the current model is not well suited to look at such issues because it does not appear to make sense to hedge bets by diversifying the "stock portfolio" by breaking up homogeneous fishing areas.

In order to get a better understanding of marine reserves it will be necessary to expand the current analysis in such a way that it can better address stock population dynamics and variability over space. Important items to consider include stock recruitment relationships, migration of post-larvae and of different cohorts, choice of fishing location based on relative catchabilities, stock densities, and travel costs, and stochasticity in economic, biological, and behavioral parameters. In the course of this work it would be interesting to see if there are analogues to the comparisons of status quo and marine reserves sustainable yield curves and the minimum positive stock size that follow from the Schaefer model.

Appendix

The expression for X_m' can be obtained by setting equation (9) equal to zero.

$$G_m(X_m) - M(X_{og}, X_m, m, Z) = 0$$
$$rX_m[1 - X_m/mK] - Z[(1-m)X_m - mX_{og}] = 0$$

Performing some algebraic manipulations and collecting terms produces

$$aX_m^2 + bX_m + cX_{og} = 0 \qquad \text{(A1)}$$

where $a = -r/mK$
$b = r - Z(1-m)$
$c = Zm$

Using the equation for the solution of a quadratic function, the relevant solution for X_m is:

$$X_m'(X_{og}) = [-b - (b^2 - 4acX_{og})^{½}]/2a \qquad \text{(A2)}$$

This will provide the positive value of X_m' when X_{og} is positive and the non-zero solution when X_{og} equals zero. With reserves, X_{og} can range between 0 and $(1-m)K$. When X_{og} equals zero, the solution to equation A2 is

$$X_m'(0) = -b/a = mK[1 - Z(1-m)/r] \qquad \text{(A3)}$$

This is an important relationship because it shows the equilibrium stock size in the reserve in the extreme case where the total stock in the fishable area is harvested every period. It can be seen that when Z= 0 (i.e., when there is no migration) the lowest possible equilibrium stock size in the reserve is mK, which is its biological carrying capacity. When Z is greater than 0, the lowest possible equilibrium stock size will be less than mK. In fact X_m' will equal zero when $Z = r/(1-m)$. When $Z > r/(1-m)$ the solution to A3 will be negative, which means that the other solution to the quadratic equation, which is this case is zero, becomes operative.

Looking at things from the other way around, this means that there is a critical reserve size for any Z that will guarantee that the lowest possible equilibrium stock size in the reserve is positive. This critical reserve size can be described as follows.

If $Z \leq r$, m must be greater than zero.
If $Z > r$, m must be greater than $1 - r/Z$.

As Z approaches 1, the critical m approaches 1-r. See the discussion of sustainable yield curves in the text.

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