

# AN EXPLORATION OF THE NATURE OF ATLANTIC TUNA MIXING

SCRS/1995/090

Col.Vol.Sci.Pap. ICCAT, 45 (2) : 173-181 (1996)

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## SUMMARY

Recent SCRS Reports have attempted to examine the effects of mixing between eastern and western Atlantic bluefin tuna on the assessment process. However, the complexity of mixing behavior is not yet well known. For example, the term "mixing" encompasses the rate of movement from one side of the ocean to the other, the rate of return of those fish that move, and the reproductive behavior of fish that cross. As an initial exploration, a four-component model is introduced based upon simple logistic dynamics (i.e. a four-box production model) and simple parameterizations. The model is not suggested for assessments, but rather to introduce the qualitative response of the stock dynamics to various mixing hypotheses. Results are used to suggest important research questions and the interaction of research priorities with management objectives.

## RESUMÉ

Des rapports récents du SCRS tentaient d'étudier l'incidence du mélange de thon rouge entre l'Atlantique est et ouest sur les processus d'évaluation. Toutefois, la complexité du comportement des échanges n'est pas bien connue. Par exemple, le terme "mélange" englobe le taux de déplacement d'un côté à l'autre de l'océan, le taux de récupération des poissons qui se déplacent et le comportement reproducteur des poissons qui traversent l'océan. En tant que première tentative, on introduit un modèle à quatre composantes fondé sur une dynamique logistique simple (c'est-à-dire un modèle de production à quatre cases) et des paramétrisations simples. Le modèle n'est pas avancé pour les besoins des évaluations, mais plutôt pour incorporer la réaction qualitative de la dynamique des stocks à diverses hypothèses concernant le mélange. Les résultats sont utilisés pour suggérer des questions de recherche importantes et l'interaction des priorités de recherche et des objectifs de gestion.

## RESUMEN

Recientes informes del SCRS tratan de examinar los efectos de la mezcla entre el atún rojo del Atlántico este y oeste en el proceso de evaluación. No obstante, la complejidad del comportamiento de mezcla aún no se conoce bien. Por ejemplo, el término "mezcla" abarca la tasa de movimiento de un lado del océano al otro, la tasa de regreso de aquellos peces que se desplazan y el comportamiento reproductivo de los peces que cruzan la mar. Como exploración inicial, se introduce un modelo de cuatro componentes basado en una simple dinámica logística (es decir, un modelo de producción de cuatro compartimentos) y conversión simple de parámetros. No se sugiere este modelo para evaluaciones, sino para introducir la respuesta cualitativa de la dinámica del stock a varias hipótesis de mezcla. Los resultados se emplean para sugerir importantes cuestiones de investigación y la interacción de las prioridades de investigación con los objetivos de ordenación.

## INTRODUCTION

Bluefin tuna movement between the western Atlantic and the eastern Atlantic plus Mediterranean (termed "east" in this paper) has been considered by SCRS for several years (Nichols 1980, Butterworth and Punt 1993, NRC 1994). However, the movement models chosen to be examined have been limited in their scope. Indeed, examination of the tagging data relative to movement showed that seemingly minor changes in analytical assumptions could lead to a large change in estimated movement rates (Turner and Powers 1994). Therefore, it has been difficult to use this information to discriminate between both the rates of movement and the nature or reason of movement. Additionally, the implications of movement to the population dynamics and management of Atlantic bluefin tuna vary depending upon the reproductive behavior of fish that move. Management strategies for stocks with movement between them and the definition of maximum sustainable yield (MSY) in such situations still need to be determined.

There have been several recent efforts to address movement rates in fish stocks both in terms of estimation (Schwarz *et al.* 1993), effects on catch-at-age analyses (Quinn *et al.* 1989) and on management strategies (Fahrig 1993). However, each of these has used relatively simplistic models of movement and has ignored implications of reproductive behavior that such movements might have. Therefore, in this paper I attempt to address the qualitative effects of more detailed movement scenarios and reproductive behavior through simple extensions to a standard production model. It is not expected that this approach should be used for assessment purposes. However, the analyses herein are useful in determining likely responses of bluefin to several different movement scenarios and will be useful in setting some research priorities.

## MODEL

The model by which I have chosen to examine the effects of movement rates and reproductive behavior is based upon the standard logistic equation from which production models arise, i.e.  $dP/dt = aP - bP^2$ , where P is biomass and a and b are parameters. However, the model is disaggregated into four biomass components, the reproductive parameters are disaggregated from the growth and natural mortality parameters, and both initial movement and return rates are added.

$$\begin{aligned} \frac{dW_w}{dt} &= \begin{array}{l} \text{growth/mortality} \\ aW_w - bW_w^2 - bW_wW_e \end{array} + \begin{array}{l} \text{repro of west origin fish} \\ r_wW_w - s_wW_w^2 - q_wW_wW_e \end{array} \\ &+ \begin{array}{l} \text{repro of east origin fish} \\ r_eW_e - s_eW_e^2 - q_eW_eW_w \end{array} - \begin{array}{l} \text{fishing} \\ F_wW_w \end{array} - \begin{array}{l} \text{movement} \\ cW_w \end{array} + jE_w \\ \\ \frac{dW_e}{dt} &= \begin{array}{l} \text{growth/mortality} \\ aW_e - bW_e^2 - bW_eW_w \end{array} - \begin{array}{l} \text{fishing} \\ F_eW_e \end{array} + \begin{array}{l} \text{movement} \\ dE_w \end{array} - iW_e \\ \\ \frac{dE_w}{dt} &= \begin{array}{l} \text{growth/mortality} \\ gE_w - hE_w^2 - hE_eE_w \end{array} - \begin{array}{l} \text{repro of east origin fish} \\ u_eE_e - v_eE_e^2 - p_eE_eE_w \end{array} \\ &+ \begin{array}{l} \text{repro of west origin fish} \\ u_wE_w - v_wE_w^2 - p_wE_wE_e \end{array} - \begin{array}{l} \text{fishing} \\ F_eE_e \end{array} - \begin{array}{l} \text{movement} \\ dE_e \end{array} + iW_e \\ \\ \frac{dE_e}{dt} &= \begin{array}{l} \text{growth/mortality} \\ gE_e - hE_e^2 - hE_wE_e \end{array} - \begin{array}{l} \text{fishing} \\ F_eE_w \end{array} + \begin{array}{l} \text{movement} \\ cW_w \end{array} - jE_w \end{aligned}$$

Note in the above that the components of the differential equations have been annotated. The parameter definitions are:

$W_w, W_e$  = biomass of fish in the west that originated in the west, east  
 $E_w, E_e$  = biomass of fish in the east that originated in the east, west

$F_w, F_e$  = fishing mortality rate on fish in the west, east

a, b, (g, h) = growth and natural mortality parameters for fish in the west (east)

$r_w, s_w, (r_e, s_e)$  = reproductive parameters of fish in the west that originated in the west (east)

$u_w, v_w, (u_e, v_e)$  = reproductive parameters of fish in the east that originated in the east (west)

$q_w, q_e$  = interaction effect on reproduction of fish in west that originated in the west from fish in the west that originated in the east, west

$p_w, p_e$  = interaction effect on reproduction of fish in east that originated in the east from fish in the east that originated in the west, east

d = rate of movement of eastern fish that originated in the east to the west

c = rate of movement of western fish that originated in the west to the east

j = rate of return of eastern fish that originated in the west to the west

i = rate of return of western fish that originated in the east to the east

The above model assumes that factors affecting growth and mortality of fish in the west (or east) act the same on those fish regardless of their origin and that production due to growth and mortality is communicative:  $[dW_w(a,b)/dt + dW_e(a,b)/dt = a(W_w + W_e) - b(W_w + W_e)^2]$  and  $[dE_w(g,h)/dt + dE_e(g,h)/dt = g(E_w + E_e) - h(E_w + E_e)^2]$ . Hence, the focus of this analysis on the effects of movements on reproductive behavior, rather than growth and mortality.

The model was parameterized in order to qualitatively examine the response of the populations to movement and reproductive behavior. There is no expectation on my part that the parameters chosen are accurate or precise; however, they do provide a qualitative means of comparison for examining research and management priorities. The model was parameterized in a simple manner by first looking at the components of east and west, if there were no mixing. The parameter chosen were as follows:

- 1) Equilibrium biomass in the east when there is no mixing and no fishing (in either the east or west) is four times the equilibrium biomass in the west (when  $c=d=i=j=F_w=F_e=0$ , then  $W_w=1$  and  $E_e=4$ );
- 2) Optimum fishing mortality rates (that which produces MSY) in the east and west (with no mixing) were equal to each other at a value of 0.2 ( $F_{opt_w} = F_{opt_e} = 0.2$ );
- 3) When biomass is very small one third of the production comes from growth and mortality factors while two thirds comes from reproductive factors for both the east and west  $[a/(a+r_w) = g/(g+u_e) = 1/3 = B]$ ; see Figure 1);
- 4) The biomass in equilibrium with no mixing and no fishing where net growth and mortality effects are zero is 80% of the biomass where net growth, mortality and reproduction effects are zero  $[(a/b) = T(a+r_w)/(b+s_w)]$  and  $(g/h) = T(g+u_e)/(g+v_e)$ ;  $T=0.8$ ; see Figure 1).

From the above, the no mixing model can be parameterized by:  $a = 2 B F_{opt_w}$ ;  $b = (2 B F_{opt_w})/T$ ;  $r_w = 2 (1-B) F_{opt_w}$ ;  $s_w = 2 (T-B) F_{opt_w}/T$ ;  $g = 2 B F_{opt_e}$ ;  $h = (2 B F_{opt_e})/(4T)$ ;  $u_e = 2 (1-B) F_{opt_e}$ ; and  $v_e = 2 (4T-4B) F_{opt_e}/(4T)$ ; see Figure 1.

Two reproductive models were examined in this analysis: R1) complete reproductive mixing where every fish that moves across the ocean acts reproductively identically to those that originated on that side; and R2) no reproductive mixing with complete spawning site fidelity, where fish that move across the ocean do not contribute at all to reproduction on the other side. The parameters values for each reproductive case are:

R1) Complete reproductive mixing

$$r_e = r_w; s_e = q_w = q_e = s_w; u_w = u_e; v_w = p_w = p_e = v_e$$

R2) No reproductive mixing; complete spawning site fidelity

$$r_e = s_e = q_w = q_e = u_w = v_w = p_w = p_e = 0$$

Several movement scenarios were considered for values of the parameters  $d$ ,  $c$ ,  $j$  and  $i$ . First, since the biomass of eastern fish is considered to be much larger than that of the west, the dynamics are dominated by the east to west movement. Therefore, the following analyses focused on the east to west rate ( $d$ ) and the return rates ( $j$  and  $i$ ), rather than on the west to east rate ( $c$ ). The west to east rate ( $c$ ) was fixed at 0.02 in most of the following analyses. However, qualitatively one can interpolate the results to infer the effects of alternative values for  $c$ . Alternative values of the east to west rate examined were: 0.01, 0.05 and 0.10.

The movement models that were examined were M1) no memory, i.e. every fish that crosses acts exactly like every other fish that is on that side and will not move to the original side at a rate different than the other fish; this is model hypothesized by Butterworth and Punt (1993) and NRC (1994); M2) medium memory where a moderate proportion of the initial movers return every year ( $j=i=0.3$ ); and M3) high memory; where initial movers return at a very high instantaneous rate ( $j=i=1.0$ ). The parameters in these cases were:

	D1) <u>d=0.01</u>	D2) <u>d=0.05</u>	D3) <u>d=0.10</u>
M1) No memory	c=0.02 j=0.01 i=0.02	c=0.02 j=0.05 i=0.02	c=0.02 j=0.10 i=0.02
M2) Medium memory	c=0.02 j=0.30 i=0.30	c=0.02 j=0.30 i=0.30	c=0.02 j=0.30 i=0.30
M3) High memory	c=0.02 j=1.00 i=1.00	c=0.02 j=1.00 i=1.00	c=0.02 j=1.00 i=1.00

Results were compared to the no mixing model:

$$r_e = s_e = q_w = q_e = u_w = v_w = p_w = p_e = d = c = j = i = 0$$

Dynamic biomasses and yields were calculated using a range of fishing mortality rates using fourth-order Runge-Kutta integration techniques (James *et al.*, 1967) until equilibrium was achieved (annual change in biomass less than 0.05%)

## RESULTS

The equilibrium yield in the west and the sum of the yield in the west with yield in the east for a matrix of  $F_w$  and  $F_e$  ranging from 0 to 0.475 were calculated. These were calculated for the combinations of reproductive models R1) and R2); movement models M1) and M2); and east to west rates of  $d=0.01$ ,  $d=0.05$  and  $d=0.10$ . Selected parameter combinations were plotted (Figure 2).

Plots of equilibrium yield in the west versus fishing mortality rate in the west ( $F_w$ ) for fixed levels of eastern fishing mortality rate ( $F_e$ ) and for  $d=0.01, 0.05, 0.1$ , the two reproductive models and the movement memory models of M1 and M2 are given in Figure 3 (for M1) and Figure 4 (for M2).

Plots of equilibrium biomass of western origin fish in the west versus fishing mortality rate in the west ( $F_w$ ) for fixed levels of eastern fishing mortality rate ( $F_e$ ) and for  $d=0.01, 0.05, 0.1$ , the two reproductive models and the movement memory models of M1, M2 and M3 are given in Figure 5 (for M1), Figure 6 (for M2) and Figure 7 (for M3).

Figure 8 gives the equilibrium west to east mixing rate (both initial movement ( $c$ ) and returns ( $d$ )) versus fishing mortality rate in the west ( $F_w$ ) for fixed levels of eastern fishing mortality rate ( $F_e$ ) and for  $d=0.01, 0.05, 0.1$ , the two reproductive models and the medium memory movement model of M2.

Figure 9 gives the equilibrium proportion of western origin fish in the west versus fishing mortality rate in the west ( $F_w$ ) for fixed levels of eastern fishing mortality rate ( $F_e$ ) and for  $d=0.01, 0.05, 0.1$ , the two reproductive models and the no memory movement model (M1).

Figure 10 gives the equilibrium net mixing rate from west to east (including the net effects of parameters  $d$ ,  $c$ ,  $j$  and  $i$ ) versus fishing mortality rate in the west ( $F_w$ ) for fixed levels of eastern fishing mortality rate ( $F_e$ ) and for  $d=0.01, 0.05, 0.1$ , the two reproductive models and the no memory movement model (M1).

#### DISCUSSION AND CONCLUSIONS

The reproductive behavior is very important if there is a management concern to maintain a viable western spawning biomass (Figures 5-7). Questions of spawning fidelity (models R1 versus R2 or some intermediate model) qualitatively change the response of the populations to fishing mortality. For example if there is no reproductive mixing (model R2), the western origin biomass in the west is always less than the no mixing model for a given level of fishing mortality rate, even for very high movement rates. Thus, if risk to the western spawning population is of great concern to management, then research approaches that address the spawning behavior of the western spawners are paramount.

If the management objective is to maintain an adequate yield level in the west and the fishing mortality rate in the east is stable, then it is more important to know the east to west movement rate and to some extent their return rate than the spawning behavior (Figures 2-4). This is because the western yield may be maintained even with little to no western spawning.

There are situations in which MSY for the east and west combined would be defined by high western fishing mortality rates and low eastern fishing mortality rates (Figure 2). These occur when the east to west movement is high. However, the yield under those conditions is only marginally better than several other  $F_w$  and  $F_e$  combinations. Maximum yield in the west can only occur when eastern fishing mortality rate is zero (for the parameter cases tested here).

If the east to west movement was moderately high ( $d=0.05$  in this parameterization) in the periods of low fishing in the east and west and movement followed the no reproductive fidelity, no memory models, then the western spawning biomass would have disappeared (Figure 5), i.e. there would be no production of western type fish; all the western reproduction would be coming from fish originating in the east and that level would not lead to any net maintenance of a western population. This argues against continuous large east to west movements for all years and ages throughout history, if there has been a western population. Alternatively, this would argue that there is just one population (no west versus east).

Interpretation of movement rates from west to east change considerably depending upon the memory model and the east to west rate (Figure 8). The west to east movement can be equal to 10% or higher, even when the initial rate  $c$  is equal to 0.02. Therefore, if one were to use conventional tagging data to determine the rate of movement and got an estimate of 10% or more, then one could still not use this information to discriminate between the components of initial movement ( $c$ ), return movement ( $i$ ) and the effect of initial east to west movement ( $d$ ) upon the results. Similarly, the net movement rate (west to east) arising from all rates ( $c$ ,  $d$ ,  $j$  and  $i$ ) can be very different than the initial rate  $c$  (Figure 10). Thus, interpretation of conventional tagging data can be very misleading for many types of movement behavior.

Knowing the proportions by origin (Figure 9) are not particularly helpful in defining initial and return movement rates or in defining the reproductive model structure. Nevertheless, if mixing proportions were known, then catches could be assigned to eastern and western "types" regardless of where they occurred. Then assessments could be conducted on the "type" populations, rather than on the "geographical area" populations, as is done now. However, this latter strategy assumes that we can monitor indices of abundance of western fish when they are in the east and vice versa. This may be problematical. Still, this approach avoids the problem of directly estimating initial movement and return rates.

Even if movements rates are high from east to west, if the fishing mortality rate in the east is moderate to high, there may be opportunities to increase western yield by maintaining the western fishing mortality rate at moderate levels (i.e. near levels that would produce MSY in a no mixing situation). This strategy would maintain adequate levels of western origin biomass, as well.

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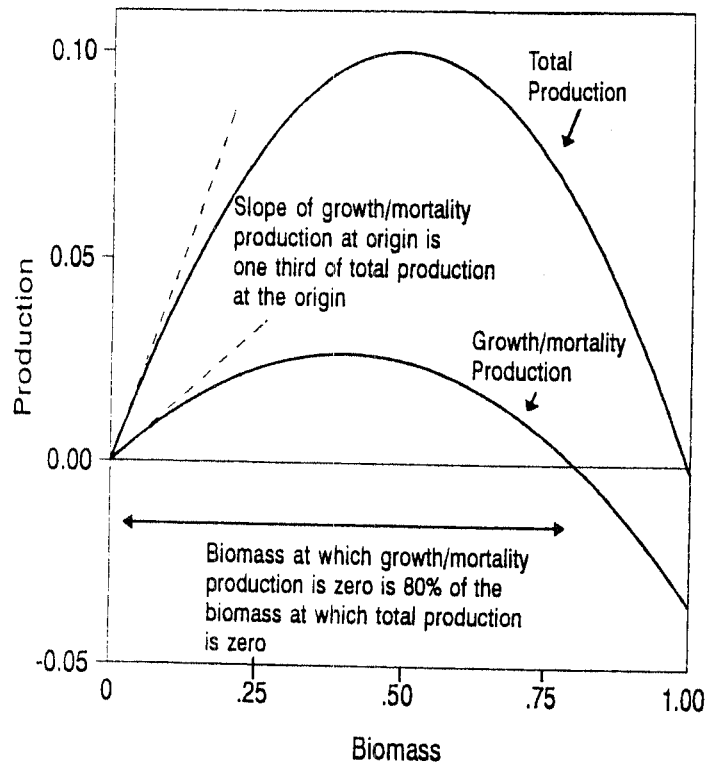


Figure 1. Parameterization of the western stock production with no mixing; the eastern stock production is equivalent but rescaled to an equilibrium with no fishing equal to 4.0

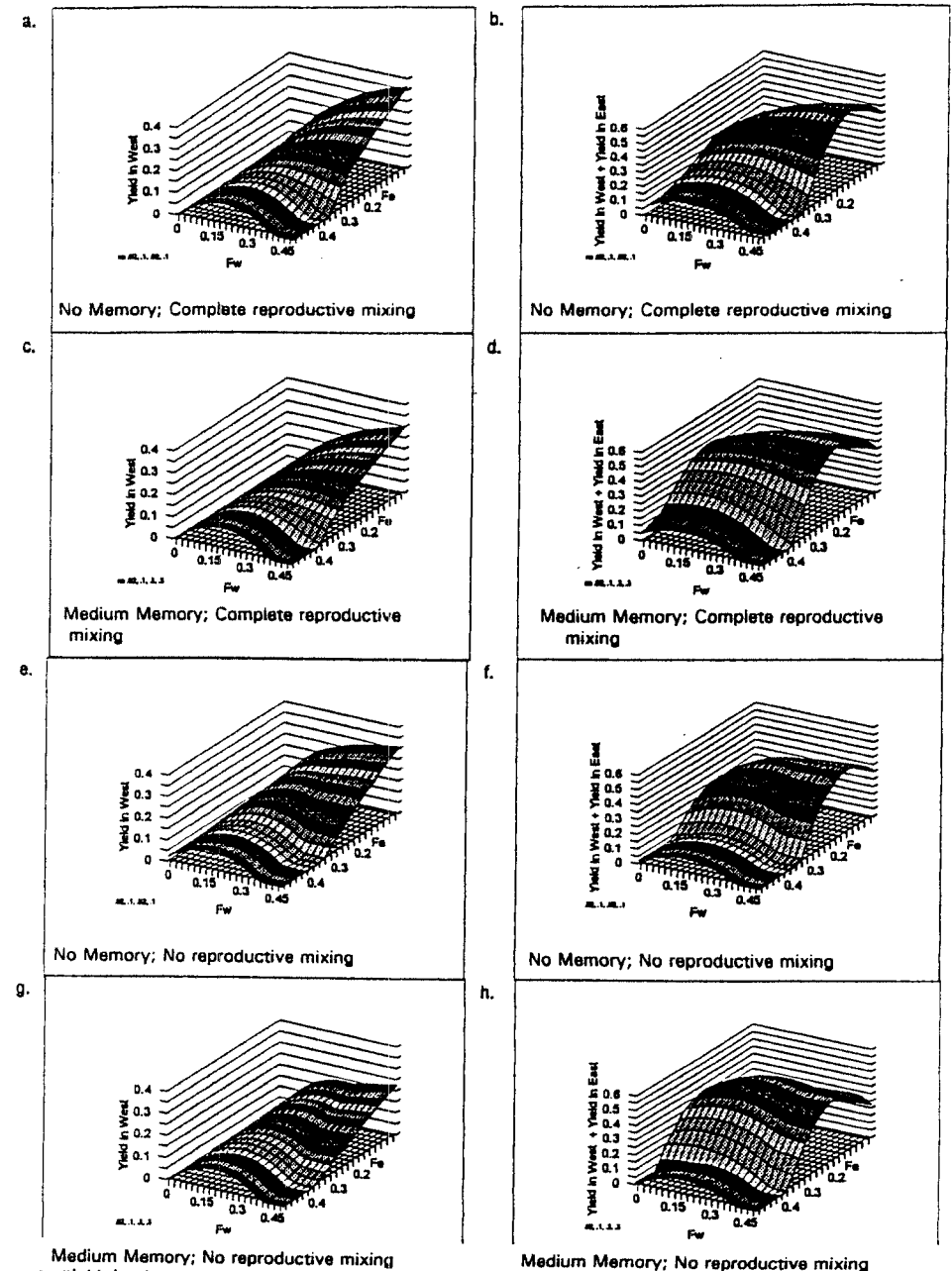


Figure 2. Yield in the west and combined east plus west yield versus east and west fishing mortality rates ( $F_E$  and  $F_W$ , respectively) using initial east to west movement of  $d=1$  and initial west to east movement of  $c=0.02$ ; No memory movement has return rates the same as initial movement rates; medium memory uses return rates  $i=j=0.3$ .

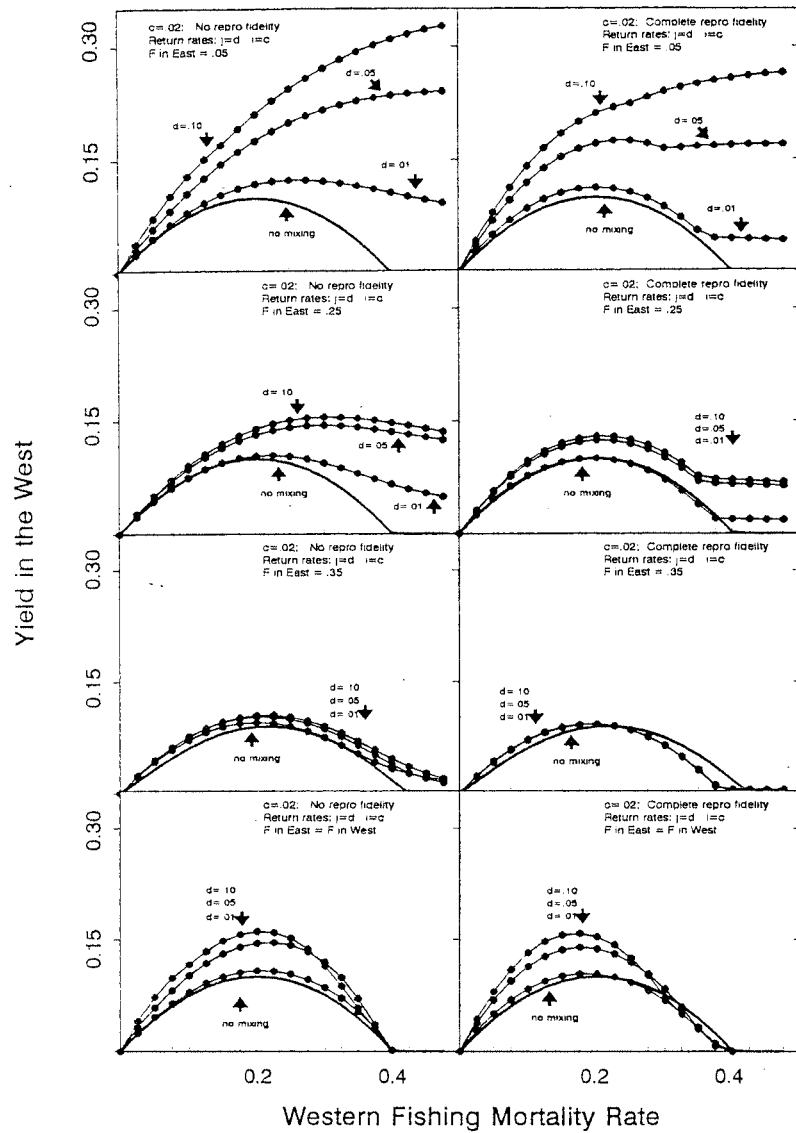


Figure 3. Yield in the west versus fishing mortality rate using alternative reproductive models and alternative movement rates; this figure uses the "no memory" return rate model where return rates are equal to the initial movement rates.

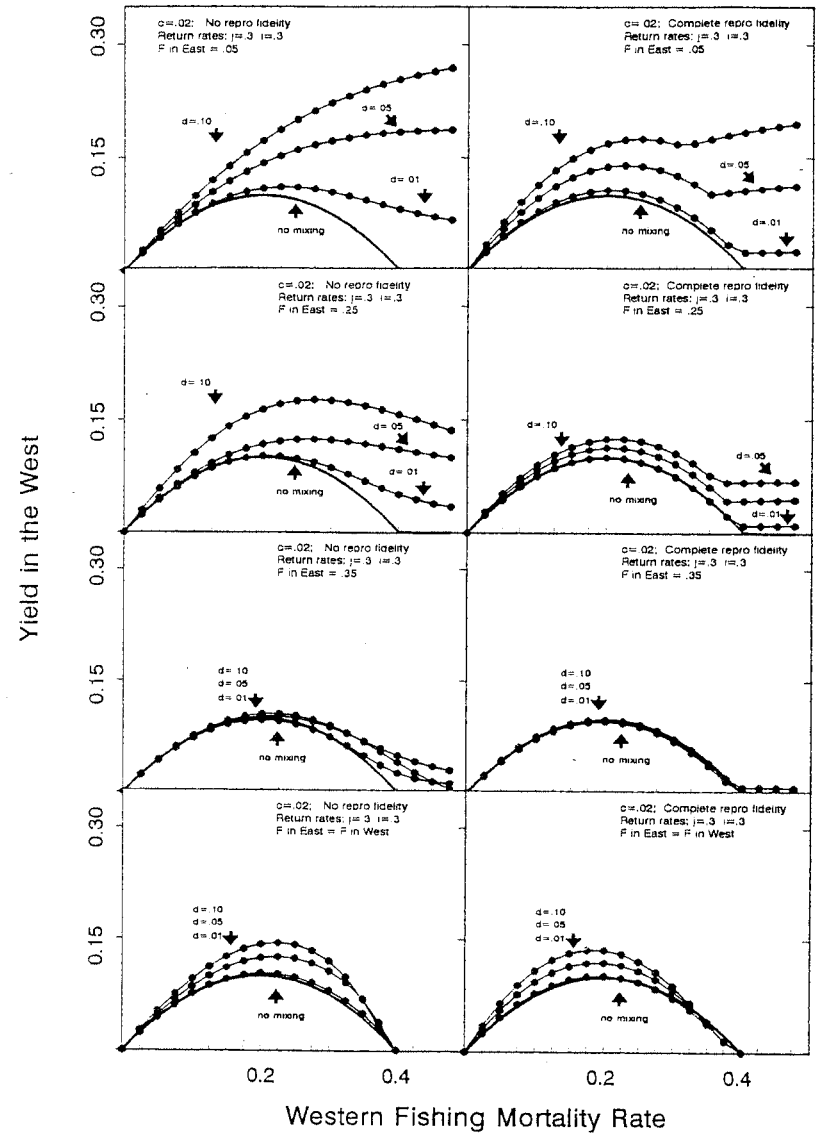


Figure 4. Yield in the west versus fishing mortality rate using alternative reproductive models and alternative movement rates; this figure uses the "medium memory" return rate model where return rates are equal to 0.3.

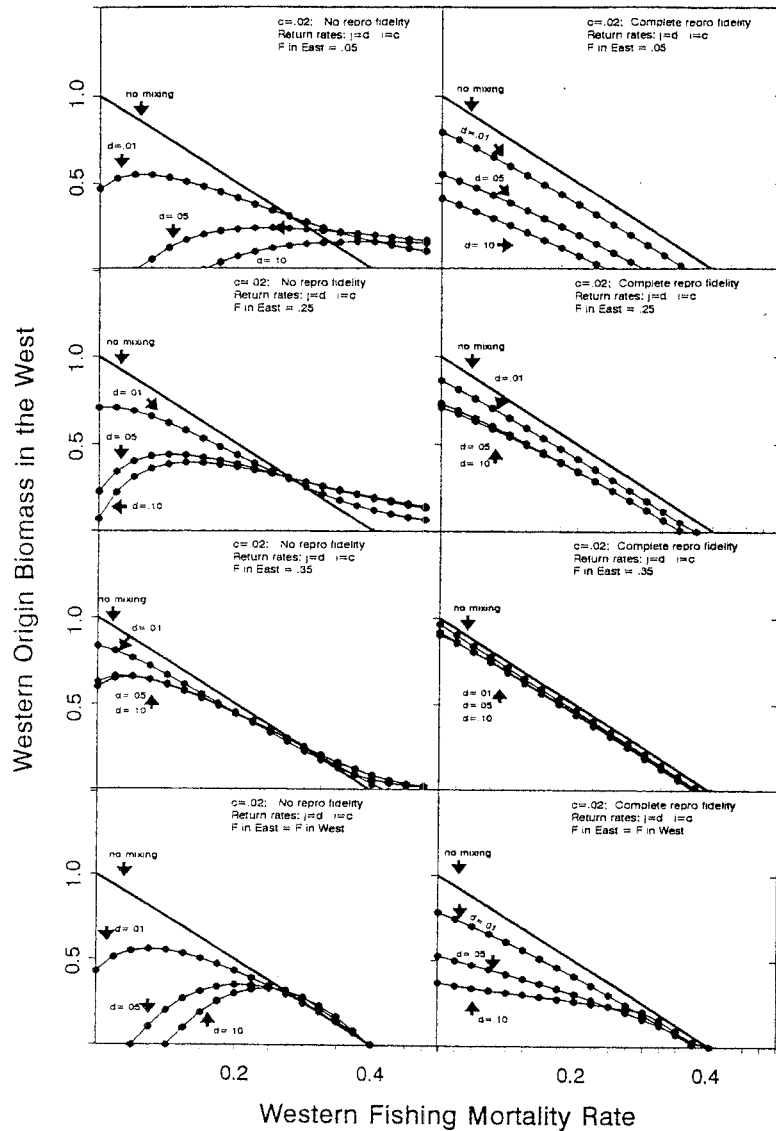


Figure 5. Western origin biomass in the west versus fishing mortality rate using alternative reproductive models; this figure uses the "no memory" return rate model where return rates are equal to the initial movement rates.

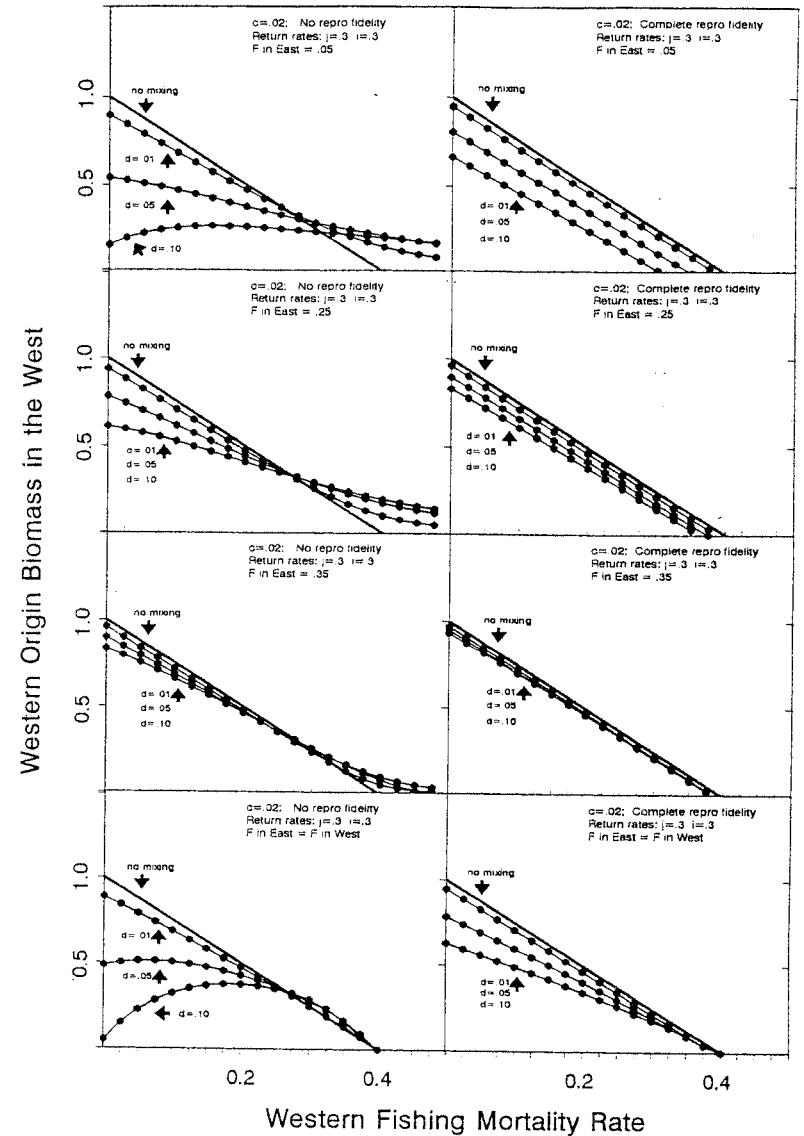


Figure 6. Western origin biomass in the west versus fishing mortality rate using alternative reproductive models; this figure uses the "medium memory" return rate model where return rates are equal to 0.3.

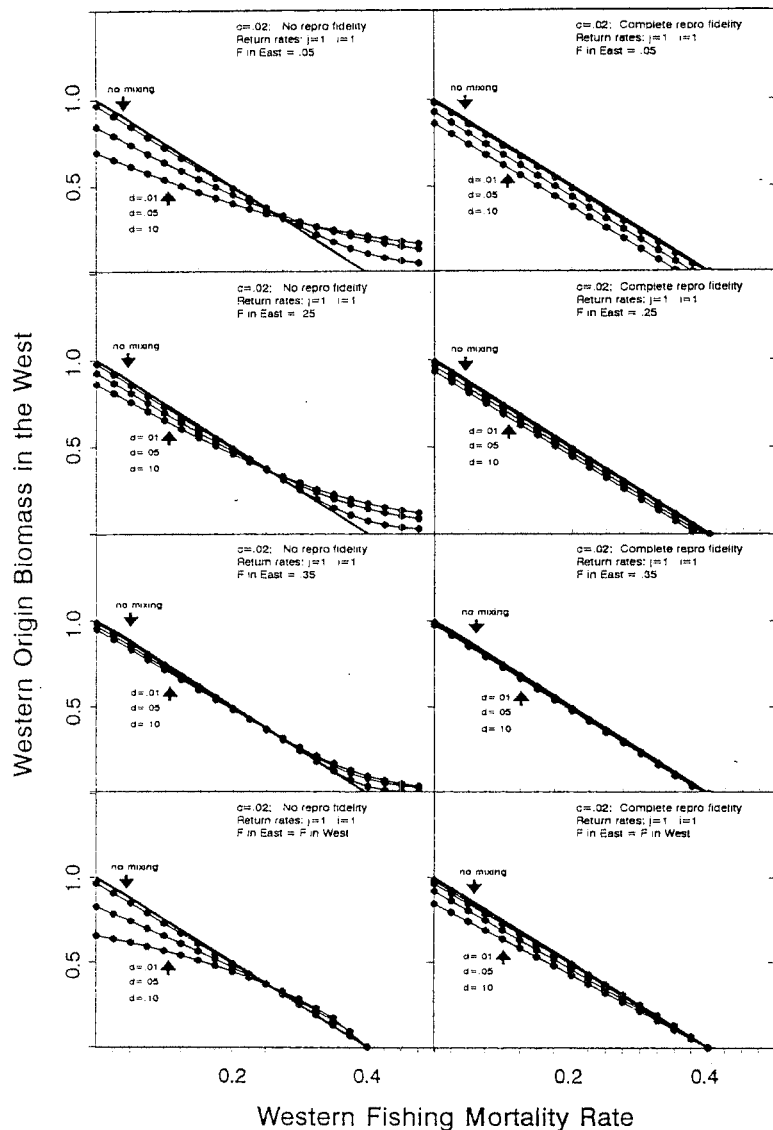


Figure 7. Western origin biomass in the west versus fishing mortality rate using alternative reproductive models; this figure uses the "high memory" return rate model where return rates are equal to 1.0.

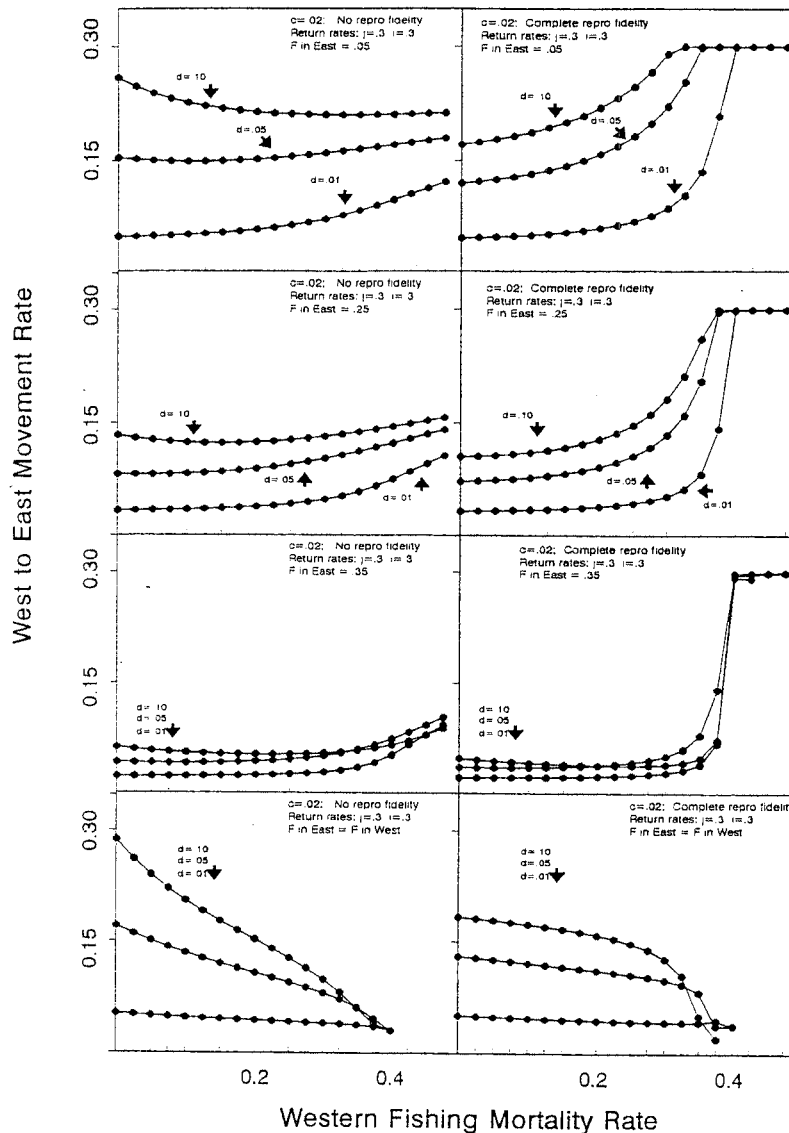


Figure 8. West to east movement rate versus fishing mortality rate using alternative reproductive models; the west to east rate includes initial movement as well as returns. This figure uses the "medium memory" return rate model where return rates are equal to 0.3.

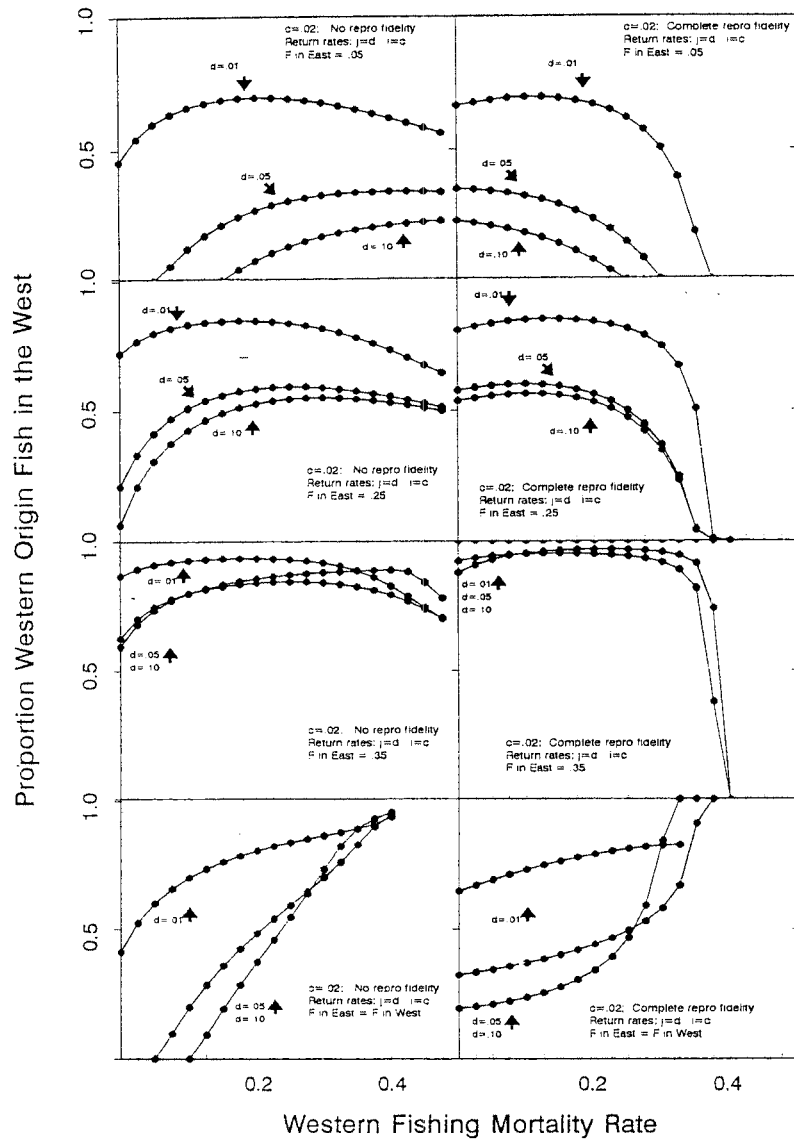


Figure 9. Proportion of western origin fish in the west versus fishing mortality rate using alternative reproductive models; this figure uses the "no memory" return rate model where return rates are equal to the initial movement rates.

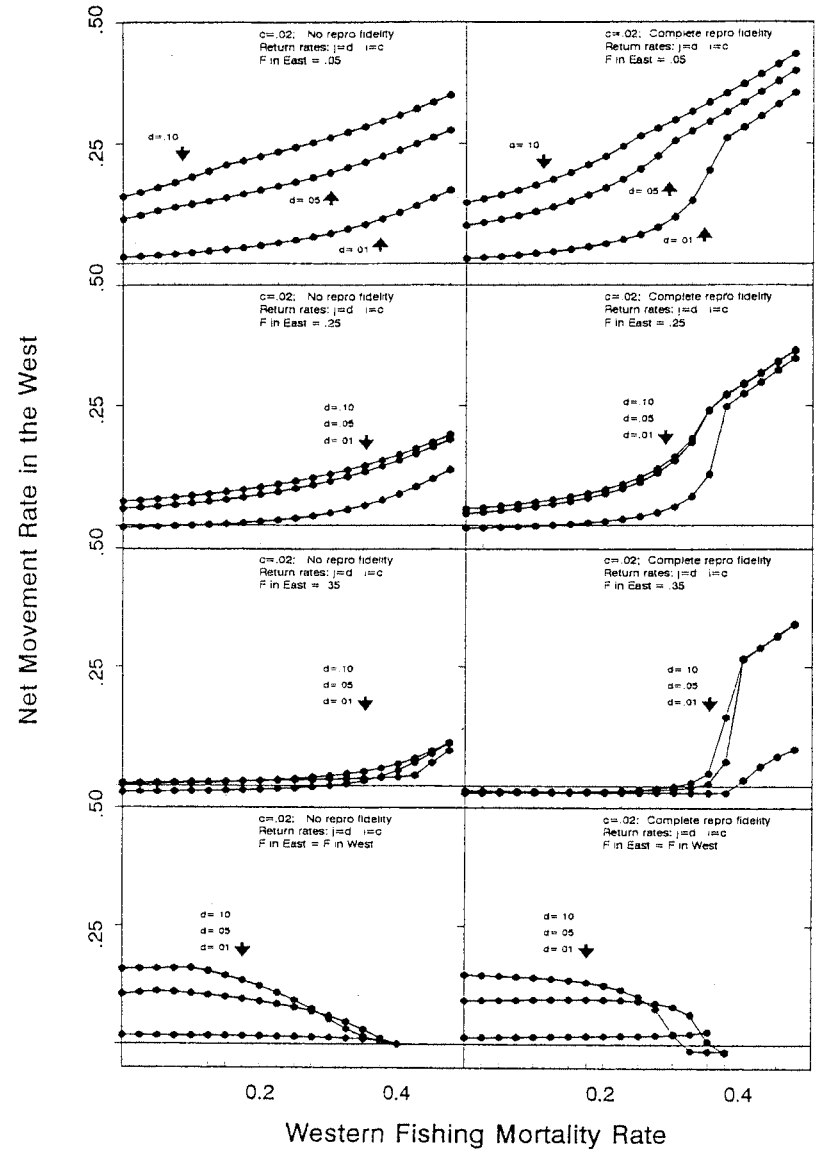


Figure 10. Net movement rate in the west versus fishing mortality rate using alternative reproductive models; net movement includes initial west to east and east to west movements plus the return movements; this figure uses the "no memory" return rate model where return rates are equal to the initial movement rates.