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Application and Testing of Principles of Stochastic Dynamic Programming in Relation to Quota Deliberations for Lake Erie Fish Populations

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INTRODUCTION

As a supplement to quota management of walleye in Western Lake Erie, the Great Lakes Fisheries Commission has supported a series of modelling studies of the population (Shuter and Koonce 1977; Shuter et al. 1979; and Koonce and Shuter 1979). These studies explored the available data base for modelling studies and reviewed possible ways of using alternative models to make management recommendations. The data base studies indicated the existence of a stock-recruitment relationship (Shuter et al 1979), and these data when combined with a simulation model confirmed extensive overfishing during the 1950's and 1960's (Shuter and Koonce 1977). Through a comparison of various procedures to set management practices, we found that deterministic and stochastic methods can lead to somewhat different management recommendations and that, in general, stochastic procedures recommend higher quotas than do deterministic models (Shuter et al. 1979; and Koonce and Shuter 1979).

The approach we take to the quota problem has been two-fold. First, we use stochastic dynamic programming (SDP) to define optimal strategies of harvesting walleye under specified conditions. This procedure has been recently used in fisheries and wildlife studies (Anderson 1976; Walters 1975; and Walters and Hilborn 1976), and we have extended it to age-structured populations with overlapping generations in the exploited fishery (Koonce and Shuter 1979). Second, we use simulation models that incorporate explicitly in stock-recruitment relationships various sources of environmental variability. The rate of spring warming, for example, has been shown to be a major source of variability for recruitment in Western Lake Erie (Busch, Scholl, and Hartman 1975), and we have shown that the rate of spring warming and adult density account for over half of the total variance in recruitment (Shuter et al. 1979; and Koonce and Shuter 1979). With this simulation model, we can explore various constant effort or SDP strategies.

Our previous studies indicated that the principles of stochastic dynamic programming offered a viable management tool and that its use could help identify some important research/monitoring problems. Our objectives in this work were thus:

1) To apply the SDP procedures to the specific management problems of walleye in Western Lake Erie at the present time;
2) To determine the limitations of the quota recommendations imposed by certain key assumptions and parameter conditions; and
3) To explore the feasibility of extending this analysis to yellow perch management and possibly joint management of perch and walleye.

ANALYSIS PROCEDURES AND RESULTS

Western Lake Erie Data

We attempted no new data analyses of walleye beyond those reported earlier (Koonce and Shuter 1979). However, we wanted to determine the sensitivity of the quota recommendations to the shape and the functional form of a stock-recruitment relationship. We also wanted to find the residual error on two basic functional forms of this relationship. Therefore, we performed stepwise, multiple correlation analysis (BMD 02R) on both a Ricker type and a log-log type stock recruitment relationship. The dependent variable for the Ricker curve was the natual logrithm of R/S and the independent variables were S and DT/T, where R is the number of recruits at age II, S is the adult stock density, and DT/T is the rate of spring warming of surface lake water during the spawning period. For the log-log curve the dependent variable was the logrithm to the base 10 of R and the independent variables were logrithm to the base 10 of S and DT/T. Table 1 summarizes the data used in the analyses, and Table 2 lists the results of the multiple correlation analyses.

These analyses do not give unequivocal support to either form of the stock-recruitment relationship. As noted before (Koonce and Shuter 1979), the Ricker curve explains slightly more of the variability in recruitment than a log-log curve, but the difference is not statistically significant. The two resulting expressions for stock-recruitment are thus

Ricker:

$$R = 0.2268\ S\ \exp[-0.284\ S + 12.00\ DT/T + E] \quad (1)$$

where E ~ N(0,1.135), and

log-log:

$$R = 0.151(S^{0.444})(32434^{DT/T})(10^{E}) \quad (2)$$

where E ~ N(0,0.180).

R and S in equations 1 and 2 are in millions of fish. In Fig. 1, is a comparison of equations 1 and 2 for E=0 and DT/T=0.215 and the observed data from Table 1.

ANALYSIS PROCEDURES

We derived optimal strategies using equations 1 and 2 in two different ways. The first was stochastic dynamic programming (Koonce and Shuter 1979), and the second was based on long term simulations at constant effort. We also checked the implications of the SDP strategies with long term simulations. The simulation model is a simple population model that represented the density of each age group (Ages I, II, III, and IV+) through time. The model formulation was

$$N(1,T) = f[S(T), DT/T] \quad (3)$$

$$N(j+1,t+1) = N(j,t)\ \exp[-U(i)q(j) - m(j)],\ j=1,2 \qquad (4)$$

$$n(4,t+1) = \sum_{j=3}^{4} N(j,t)\exp[-U(i)q(j) - m(j)],\ \text{and} \qquad (5)$$

$$S(t) = \sum_{j=1}^{4} k(j)N(j,t)\ , \qquad (6)$$

where f[S(t),DT/T] is given by equation 1 or 2, DT/T is a random variable ~N(0.215,0.0048), k(j) is the fraction of age group j that is reproductively mature, q(j) is the catchability coefficient of the age group j, m(j) is the natural mortality of age group j (assumed to be 0.218 per year for all age groups), and U(i) is the effort level specified. This algorithm was computer coded in BASIC and an example of a constant effort simulation is listed in Appendix 1. All simulations had a 50 yr adjustment period for initial condition transients.

The stochastic dynamic programming algorithm considered only four age groups (ages I, II, III, and IV+) at the spring of the year. As with Walters (1975), the SDP algorithm proceeds backwards through time. At each stage an optimal control law is calculated for each population state. In our model, this control law related annual instantaneous fishing effort, U(i), to a particular population state. The optimum effort for a particular state is determined by the value of the objective function, which includes harvest and the future value of the resulting stock the next year. The yearling density of the resulting stock, however, is a probabalistic function of the rate of spring warming. Each analysis also would depend upon a fixed catchability schedule (q(j), j=1,4) and a fixed fecundity schedule (k(j), j=1,4). Annual harvest was thus

$$H=\sum_{j=1}^{4}[U(i)q(j)/(U(i)q(j)+m(j))]N(j)[1-\exp(-U(i)q(j)-m(j))] \quad (7)$$

where the coefficients are the same as in eqs. 3 to 6. Recruitment to the yearling age group was given by the stock-recruitment relationships and the adult density as discussed above.

Because the relationship between effort and population state is a five dimensional hypervolume, direct visual representation is impossible, and a listing of the data is too cumbersome. In this report, therefore, we group ages I and II as juveniles and III and IV+ as adults. For Western Lake Erie walleye, this partitioning is not strictly correct. The current estimate of female maturity at age III is only 19% (Davies et al. 1979). However, these groupings into young and old fish allow simpler tabular summaries of effort and quota recomendations. We also adopt the later age at maturity for females as defining the maturity schedule for the population and thus have a conservative assumption about the density of the adult stock. Finally, we assumed catchability coefficients that correspond to the current regulations for walleye in Western Lake Erie. These regulations allow recruitment to the fishery of 10% of the yearlings and all of older age groups.

The formula for calculating catchability, q(j), from vulnerability to gear, V, was

$$q(j) = -\log[1 - V\ (1 - \exp(-1))]$$

For yearlings, the catchability coefficient is thus 0.0653, and all other age groups have a coefficient of 1.

To address current management questions for this population, we had to make several modifications of the SDP algorithm (Koonce and Shuter 1979). A major change involved a modification of the interpolation procedure for interpreting future value of a population state. More minor modifications included the development of alternative versions of the model that varied in the nature of their objective function. The original version maximized the quantity:

$$V = -(H - d)(H - d) \qquad (8)$$

where H was the harvest obtained from a particular stock for a given effort and d was the desired harvest. As discussed by Walters (1975), this expression has the advantage of pursuing a range of strategies simply by varying d. At very high values of d, this expression allows maximization of harvest, and lower values would allow the development of strategies for minimizing variance about a desired harvest. The modifications of this objective function expanded the range of harvest and population attributes for which optimization could be performed. In additon to numerical harvest, therefore, the new versions allowed optimization by equation 8 for the biomass of the harvest and the numerical abundance of the fishable stock. Finally, we programmed versions that differed in the type of stock-recruitment relationship.

Using these different versions of the model, we settled on four classes of parameter sets (Table 3) using both stock-recruitment relationships (i.e. eqs. 1 and 2). Control laws derived for the log-log stock-recruitment relationship, however, were unsatisfactory because of the effort grid we used in the parameter set, and we do not discuss them further. The first of the four classes of parameter sets was a minimization of variance series for numerical harvest. By varying the desired harvest from an unattainable 50 million to 1 million fish per year, we wanted to examine the possible trade off between size and variability of annual harvest. The second class of parameter sets was a single analysis of a strategy to maximize the biomass of the harvest. The third parameter set class was another series, but designed to examine the trade off between size and variability of the fishable stock. Finally, we used the fourth class of parameter sets to determine the effects of various maturity schedules on strategies that seek to maximize numerical harvest. Codes and key parameter values are summarized in Table 3 for all for sets of parameters.

RESULTS OF MODEL ANALYSES

We summarize the optimal control laws for the various SDP strategies (Table 3) in two ways. First, we examine the optimal effort for various juvenile states, and second, we present the quotas that follow from the strategies for various combinations of adult (ages III and IV+) and juvenile (ages I and II) densities. The summaries of these strategies are organized as follows: Tables 4 to 8 contain the strategies to minimize variability of numerical catch about various desired harvest levels; Table 9 lists the optimal exploitation for maximizing the biomass of the harvest; Tables 10 to 12 refer to the strategies to minimize variability of the fishable stock about specified levels; and Tables 13 and 14 with Table 8 reveal the effect of variation in the fraction of the three-year old females that are reproductively mature.

Simulations of the SDP strategies indicate substantial difference in fishery performance depending upon the specific strategy. As indicated by the mean and standard deviation of effort, annual harvest, and annual spring adult density, which is defined by the maturity schedule assumed in the parameter set, these differences may have a wide range (Table 15). For the current maturity schedule of walleye in Western Lake Erie, the results suggest that, once the population stabilizes to optimal exploitation, it can provide a long term average yield of 3.5 million fish per year. Furthermore, the trade-off between mean annual harvest and variance of annual harvest seems to indicate that variability increases markedly beyond a mean annual harvest of 2.5 million walleye (Fig. 3). In comparing harvest or biomass of harvest, the biomass strategy is clearly superior in both harvest characteristics and residual adult density, but it accomplishes this better performance at about the same effort. This strategy difference stems from a lower reliance on juvenile harvest (compare Tables 8 and 9). As one might expect, mean annual yields and effort increase with the fraction of 3 yr-old females mature. Finally, there seems to be little effect on mean annual harvest of minimizing variability about a fishable stock between 5 and 10 million fish. However, to maintain current success rates of the sports fishery with a fishable stock of about 15 million would mean far lower yields in a near steady-state population.

These SDP strategies used an effort interval of 0.15 for a range of 0 to 3.0 per year. Where mean annual efforts fall in the range of 0.0 to 0.45 per year, the coarseness of the available effort controls could be responsible for the irregular quota recommendations from these strategies (cf. Tables 4, 5, 6, and 12). To test this possibility, we modified a parameter set (HR2L4 in Table 3) to have an effort interval of 0.05 per year. This parameter set was derived to minimize variance about a desired harvest of 3 million fish. The quota recommendations for various adult and juvenile densities was much smoother (Fig. 3) than that for the coarser effort interval (Fig. 4). The simulation performance for this modified parameter set was also better than the original (Table 15). Therefore, the derivation of SDP strategies was sensitive to the coarseness of the effort controls for some parameter conditions. For the strategies designed to maximize harvest, however, the effect appears to be minimal, and the pareto function for trade-off between harvest and variance of harvest would be only slightly modified (Fig. 2).

The SDP strategies require both historical data and current information on the state of a stock for quota recommendations. Our second procedure, required only historical data with which to derive a stock-recruitment relationship and the characteristics of the random environmental variation about this relationship. Our use of the long term, stochastic simulations with such a model (eqs. 3-6) has a strong relationship to those used in traditional fisheries science (eg. Ricker 1958). The recent demonstration of the extension of age-structured populations with overlapping generations to these traditional models (Deriso 1979) emphasizes the connection. Using the current definition of fishable stock and a maturity schedule in which 19% of the 3 year old and all older walleye were reproductively mature, we obtained harvest versus effort curves for each of the stock-recruitment relationships (eqs. 1 and 2) for various stochastic versions. For the Ricker relationship, we found that the fully stochastic version (incorporating both explained variance and unexplained variance) gave higher yields than the version incorporating only the variance explained by the rate of spring warming (Fig. 5). Both of these stochastic versions predicted greater sustainable yields than a simple deterministic model, which assumed a constant rate of warming of 0.215 deg C per day (the long term mean for Western Lake Erie, Shuter et al. 1979). Nevertheless, these different versions indicated an optimal effort of 0.4 per year, which is quite close to the long term average of the SDP simulations for maximal harvest (Table 15). The alternate log-log stock-recruitment relationship showed a similar trend between the stochastic version and the deterministic version. In contrast to the Ricker relationship, however, the optimal effort was lower (about 0.2 per year) and the mean annual yields were lower by nearly half (Fig. 6). These low optimal efforts undoubtedly contributed to the failure of the SDP algorilthm for the log-log relationship with the coarse effort interval. Other characteristics of the simulated population behavior at optimal efforts are summarized in Table 16.

DISCUSSION OF WALLEYE MANAGEMENT OPTIONS

Our earlier studies indicated that current quotas for walleye harvest in Western Lake Erie were conservative with respect to those that utilize contemporary information on the state of a stock (Koonce and Shuter 1979). This conclusion was based on some differences in the various quota derivation procedures that we traced to differences in fundamental assumptions. Several aspects of the SDP algorithm and parameter condition, however, needed more careful examination before applying these procedures to the Western Lake Erie walleye population.

In this study, we feel that we have fully applied the SDP algorithm and stochastic simulation models to the contemporary problem of walleye management. Our procedures are designed to yield a quota recommendation given the current state of the stock. However, both procedures actually calculate optimal efforts for a defined catchability schedule and compute the quota as a consequence of the effort. In this aspect, both quota setting procedures are in substantial agreement. For maximum sustainable harvest, which is the only valid comparison of the SDP and constant effort strategies, both procedures indicated about the same effort. Furthermore, in terms of the trade-off between mean annual harvest and variability of harvest, the constant effort strategies are on the pareto frontier established by the SDP strategies.

Despite the apparent agreement on long-term optimal effort, the constant effort and SDP strategies differ greatly in contemporary quota recommendations (Table 17). The long-term agreement, of course, is based on the behavior of a simulated population that has adjusted to a given exploitation scheme. In the case of the SDP strategies, the effort and thus harvest varies with the state of the stock. Clearly in Tables 8 and 9, which are the SDP strategies designed to maximize harvest, some population states can withstand very high exploitation rates for a short period of time. This variable optimal effort characteristic of the SDP strategies results in improved simulation performance of the adult stock. Although the mean adult densities are greater for the constant effort strategy than for either of the above SDP strategies, the variability of the adult density is lower and thus the population is less likely to fall into occassional low density conditions in which it becomes more vulnerable to a variety of other stresses (e.g. Beddington and May 1977; and Peterman et al. 1979). Because the population has not adjusted to optimal exploitation, therefore, the SDP strategies might be more useful to bring the walleye population into a managed state. However, the issue of how conservative a particular strategy is depends upon a judgement about wheather the stock is currently overexploited. Again the SDP strategies are useful in this case because they are sensitive to this issue.

One problem with even projecting populations that have adjusted to exploitation is the historically variable age of reproductive maturity of females. The fraction of three year old females that were mature varied from 100% to 19% (Wolfert 1969; and Davies et al. 1979). We explored the effects of this variabiltiy in three-year old maturity in a series of simulations of SDP strategies (Table 15). As the fraction of mature three-year olds increases from 19% to 100%, the optimal effort increases from 0.45 to 0.71 per year. These increases result in slightly elevated harvest and higher residual adult densities. The SDP strategies, therefore, do allow adjustment for variable maturity schedules, and this information is vitally important to successful management.

This discussion of quota setting procedures and consequences has so far focused only on the Ricker type stock-recruitment relationship. Although we did not pursue the SDP strategies for the log-log relationship, we assume that the general agreement between constant effort and SDP long-term effort simulations apply to this relationship as well, and we can make some useful comparisons between the constant effort strategies for each of the stock-recruitment relationships.

The sensitivity of optimal exploitation strategy to the functional form of the stock-recruitment relationship is a serious obstacle to quota management. Constant effort simulations (Figs. 5 and 6) suggested that the form of the stock-recruitment relationship greatly influences the expected harvest and population response to exploitation. Because no a priori statistical basis exists for selecting either equation 1 or 2, we really only have biological reasons for preferring equation 1 (Koonce and Shuter 1979). However, each of the stock-recruitment relationships has different parameter estimation problems. For the Ricker curve (eq. 1), the lower number of observations at high stock densities greatly influences the parameter values of the multiple regression (Fig. 7). The reverse situation is true for the log-log relationship (Fig. 8). While this difference in the data fitting requirements of the two models is due in part to their differences in functional form, optimal effort for the Ricker model, and we presume for the log-log model, seems to be insensitive to error on the stock coefficient (i.e. the density dependent parameter; Fig. 9). The position of the maximum recruitment as a function of stock size does vary (Fig. 10), but these variations in shape of the stock-recruitment relationship seem to affect only the deterministic projections of sustainable yield (Fig. 9). Because quotas are ultimately derived from optimal effort decisions, the quota setting procedure seems less affected by the shape of a particular stock-recruitment relationship than the functional form of that relationship.

In summary, the SDP and the constant effort strategies can be applied to the quota deliberations for Western Lake Erie. The only serious difficulty is the determination of the actual functional form of the stock-recruitment relationship. For a population adjusted to any exploitation strategy, all strategies derived from a particular stock-recruitment relationship indicate the same effort over a long period of time. The two forms of the stock-recruitment relationship, however, differ markedly in the recommended quotas and effort (Table 17). Depending upon the specific objectives of management, the SDP strategies may be superior to any constant effort strategy. Furthermore, the SDP strategies allow an annual updating of recommended effort used in setting the quota and, therefore, it compensates for possible errors in the stock-recruitment relationship in situations where the population state boarders on over-exploitation.

FEASIBILITY OF EXTENSIONS TO YELLOW PERCH AND JOINT YELLOW PERCH/WALLEYE MANAGEMENT

One of the primary objectives of our study was to determine the feasibility of extending our analyses to yellow perch and to joint management of yellow perch and walleye. Work underway in Ontario suggested that a stock-recruitment relationship can be obtained for yellow perch from historical data (Petzold, personal communication). With such a relationship, we could apply our procedures directly to the yellow perch populations in Lake Erie. The analyses we have already, however, suggest some differences in the strategies for yellow perch and walleye.

Using the deterministic model results, we found that the shape of the Ricker curve did not influence optimal effort for a constant effort strategy. The optimal effort is influenced strongly by the fertility schedule and the catchability schedule for a particular population (Fig. 11). We obtained these results from a walleye stock-recruitment relationship, but if a Ricker curve can also be fitted to the yellow perch data set, the optimal efforts should be the same for given fertility and catchability schedules. In the case of Fig. 11, either earlier reproductive maturity or more age specific catchability differences for yellow perch imply a higher optimal effort for yellow perch than for walleye. These results, however, can not be applied to quota management of yellow perch without contemporary estimates of population density and age composition.

The need to consider joint management of walleye and yellow perch has been well illustrated by the experience of walleye management in Oneida Lake (Forney 1980). Our earlier results suggested some influence of yellow perch on walleye stock-recruitment (Koonce and Shuter 1979), and we felt that our procedures could be applied to this problem. In this case, our expectations have not been fulfilled. We have found no way to simplify the walleye/yellow perch interactions to make them accessible to dynamic programming. However, our experience with the similarity of long-term behavior of SDP and constant effort strategies lends some support to pursuing these studies through simulation.

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APPENDIX 1

CONSTANT EFFORT POPULATION MODEL

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10 REM SDP SIMULATION PROGRAM FOR T1 YEARS AT OPTIMAL EFFORTS
20 REM MODIFIED 29-SEP-79 BY J. KOONCE
30 REM INTERPOLATION PROCEDURE MODIFIED 26-JUL-80
40 REM TEMPERATURE RANDOMIZATION MODIFIED 16-JUL-80
50 DIM W(4)
60 DIM P(1296)
70 DIM J(4),K(4),M(4),Q(4),N(4),S(14),R(14),D(4)
80 DIM X(31),F(4)
90 REM LENGTH OF RUN AND ADJUSTMENT PERIOD
100 DEF FNP(A1,A2,A3,A4)=A1+(A2-1)*6+(A3-1)*36+(A4-1)*216
109 REM DEFINE RUN LENGTH AND ADJUSTMENT PERIOD
110 T1=1050  T2=50
120 N8=1.00000E+30  N9=-1
130 REM READ FECUNDITY,MORT, CATCHABILITY,GRID SIZE SCHEDULES
140 FOR I=1 TO 4
150 READ K(I),M(I),Q(I),D(I)
155 F(I)=(1-EXP(-Q(I)))/(1-EXP(-1))
160 NEXT I
170 REM READ INITIAL POPULATION STATE
180 FOR I=1 TO 4
190 READ N(I)
200 N(I)=(N(I)-1)*D(I)
210 NEXT I
220 RESTORE
230 IF F7=1 GO TO 440
240 REM INPUT EFFORT ARRAY
250 PRINT "EFFORT ARRAY"  INPUT I$
260 OPEN I$ FOR INPUT AS FILE  1
270 INPUT  1,L$
280 IF L$="" GO TO 270
290 FOR I4=1 TO 6
300 FOR I3=1 TO 6
310 FOR I2=1 TO 6
320 INPUT  1,L$
330 INPUT  1,L$
340 FOR I1=1 TO 6
350 J1=I1*2-1  J2=J1+1
360 D$=SEG$(L$,J1,J2)
370 J3=I1+(I2-1)*6+(I3-1)*36+(I4-1)*216
380 P(J3)=VAL(D$)
390 NEXT I1
400 NEXT I2
410 NEXT I3
420 NEXT I4
430 F7=1
440 REM INITIALIZE SUMMATION TERMS
450 FOR I=1 TO 14
460 S(I)=0
```

```
470 NEXT I
480 REM VALUES FOR MEAN AND STD. DEV OF TEMPERATURE INCREASE
490 M9=.215
500 S=.064
510 REMRANDOMIZE
520 N=0
530 REM 150 YEAR SIMULATION LOOP
540 PRINT "STORE ANNUAL DATA";  INPUT A$  PRINT "TIME:  "CLK$
550 IF A$<>"Y" GO TO 590
560 O$=SEG$(I$,5,10)+".DJK"
570 OPEN O$ FOR OUTPUT AS FILE  2 FILESIZE 120
580 PRINT "OUTPUT DATA IS STORED IN FILE "O$
590 FOR I=1 TO T1
600 S1=0  S2=0  H=0  S3=0
610 FOR J=1 TO 4
620 REM ADULT, TOTAL DENSITY, AND FISHABLE STOCK CALCULATION
630 S1=S1+K(J)*N(J)
640 S2=S2+N(J)
645 S3=S3+N(J)*F(J)
650 NEXT J
660 IF I<=T2 GO TO 690
670 IF S1<N8 THEN N8=S1
680 IF S1>N9 THEN N9=S1
690 REM DETERMINE POPULATION STATE
700 FOR J1=1 TO 4
710 J(J1)=INT(N(J1)/D(J1))+1
720 IF J(J1)<6 GO TO 740
730 J(J1)=5
735 W(J1)=D(J1)  GO TO 750
740 W(J1)=N(J1)-(J(J1)-1)*D(J1)
750 NEXT J1
760 REM INTERPOLATION OF EFFORT
770 J3=FNP(J(1),J(2),J(3),J(4))
780 X(1)=P(J3)*.05
790 M=0
800 FOR I4=1 TO 2
810 FOR I3=1 TO 2
820 FOR I2=1 TO 2
830 FOR I1=1 TO 2
840 M=M+1
850 I5=J(1)+I1-1
860 I6=J(2)+I2-1
870 I7=J(3)+I3-1
880 I8=J(4)+I4-1
890 J3=FNP(I5,I6,I7,I8)
900 X(M)=P(J3)*.05
910 NEXT I1  NEXT I2  NEXT I3  NEXT I4
920 M2=1
930 FOR M1=4 TO 1 STEP -1
940 O1=2(M1-1)  O2=O1*2
950 M3=M2+O1-1
960 FOR M=M2 TO M3
965 Z9=J(M1)*D(M1)-N(M1)
966 IF Z9<0 THEN Z9=0
970 X(M+O2)=(X(M+O1)*W(M1)+X(M)*Z9)/D(M1)
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980 NEXT M
990 M2=M2+02
1000 NEXT M1
1010 F=X(31)
1020 IF F>3 THEN F=3
1030 REM HARVEST CALCULATION
1040 FOR J=1 TO 4
1050 H=H+(Q(J)*F/(M(J)+Q(J)*F))*N(J)*(1-EXP(-M(J)-Q(J)*F))
1060 NEXT J
1070 REM COMPUT SURVIVORS
1080 N(4)=N(4)*EXP(-M(4)-Q(4)*F)+N(3)*EXP(-M(3)-Q(3)*F)
1090 N(3)=N(2)*EXP(-M(2)-Q(2)*F)
1100 N(2)=N(1)*EXP(-M(1)-Q(1)*F)
1110 REM TEMPERATURE RANDOMIZATION
1120 R1=RND  R2=RND
1130 Z=SQR(-2*LOG(R1))*COS(2*PI*R2)
1140 T=M9+Z*S
1150 REM INSERT CORRECT STOCK-RECRUITMENT RELATIONSHIP
1160 REM RICKER CURVE
1170 S1=S1/1.00000E+06
1180 N(1)=.2828*S1*EXP(-.284*S1+11.99*T)
1190 N(1)=N(1)*1.00000E+06
1200 S1=S1*1.00000E+06
1210 IF I<=T2 GO TO 1360
1220 REM UPDATE ACCUMULATORS
1230 S(1)=S(1)+H
1240 S(2)=S(2)+H*H
1250 S(3)=S(3)+S2
1260 S(4)=S(4)+S2*S2
1270 S(5)=S(5)+S1
1280 S(6)=S(6)+S1*S1
1290 S(7)=S(7)+N(1)
1300 S(8)=S(8)+N(1)*N(1)
1310 S(9)=S(9)+T
1320 S(10)=S(10)+T*T
1322 S(11)=S(11)+S3
1324 S(12)=S(12)+S3*S3
1326 S(13)=S(13)+F
1328 S(14)=S(14)+F*F
1330 N=N+1
1340 IF A$<>"Y" GO TO 1360
1350 PRINT  2,F","S1","S2","H","T","S3
1360 NEXT I
1370 REM CALCULATION OF MEANS AND VARIANCES
1380 FOR J=1 TO 14 STEP 2
1390 R(J)=S(J)/N
1400 R(J+1)=(S(J+1)-S(J)*(S(J)/N))/(N-1)
1410 NEXT J
1420 REM PRINT RESULTS
1430 A$(1)="HARVEST"
1440 A$(3)="ADULT DENSITY"
1450 A$(2)="TOTAL DEN."
1460 A$(4)="YEARLING DEN."
1470 A$(5)="DELTA T/T"
1475 A$(6)="FISH. STOCK"
```

```
1477 A$(7)="EFFORT"
1480 PRINT T1"YEAR SIMULTION RESULTS FOR FILE:  ";I$
1490 PRINT "WITH A"T2"YEAR ADJUSTMENT PERIOD"
1500 PRINT
1510 IF F8=1 GO TO 1570
1520 PRINT "PARAMETER SUMMARY"
1530 PRINT "AGE","K","M","Q","D"
1540 FOR Z=1 TO 4  PRINT Z,K(Z),M(Z),Q(Z),D(Z)  NEXT Z
1550 F8=1
1560 PRINT
1570 PRINT
1580 PRINT "VARIABLE","MEAN","VARIANCE","STD ERROR","COEF.VAR."
1590 PRINT
1600 FOR J=1 TO 7
1610 J1=J*2-1  J2=2*J
1620 PRINT A$(J),R(J1),R(J2),SQR(R(J2))/SQR(N),SQR(R(J2))/R(J1)
1630 NEXT J
1640 PRINT "RANGE OF ADULT DENSITY:";N8;"-";N9
1650 PRINT
1660 PRINT "FINISH TIME:  "CLK$
1700 PRINT   PRINT
4000 DATA 0.0,0.218,0.0653,2E6
4020 DATA 0.0,0.218,1,2E6
4040 DATA 0.19,.218,1,2E6
4060 DATA 1,.218,1,2E6
4080 DATA 3,3,3,3
30000 END
```

Table 1. Summary of adult density, recruitment of age II individuals, and rate of water temperature increase in spring for Western Lake Erie during the period 1947-1978.

Year	Adult Density (millions)	Recruit Density at t+2 (millions)	Temperature Slope (deg C/day)
1947	9.300	5.670	0.18
1948	6.900	5.200	0.19
1949	5.560	6.100	0.21
1950	7.450	2.980	0.22
1951	7.100	2.980	0.23
1952	7.370	7.100	0.27
1953	4.790	1.200	0.18
1954	3.520	5.420	0.21
1955	5.390	2.910	0.29
1956	1.750	1.290	0.20
1957	3.320	0.434	0.21
1958	2.640	0.206	0.17
1959	0.744	3.330	0.24
1960	0.310	0.114	0.18
1961	0.103	0.414	0.24
1962	0.697	3.590	0.29
1963	0.196	0.558	0.20
1964	0.036	0.527	0.32
1965	0.320	1.970	0.36
1966	0.101	0.165	0.10
1967	0.136	0.243	0.13
1968	0.941	0.318	0.12
1969	0.237	0.973	0.24
1970	0.198	5.280	0.31
1971	0.051	0.580	0.21
1972	0.490	4.020	0.20
1973	2.650	1.270	0.17
1974	1.760	9.500	0.19
1975	2.630	5.050	0.00
1976	1.910	1.310	0.14
1977	6.240	22.100	0.27
1978	8.230	0.819	0.24

Table 2. Results of stepwise multiple correlation analysis using BMD 02R. Also indicated are the linear transformations of each of the two stock-recruitment relationships. The variables indicated are S, adult stock in millions; r, age II recruits in millions; DT/T, rate of spring warming in deg C/day; ln, natural logrithm; and log, logrithm to the base 10.

Parameter	Ricker Curve	log-log Curve
R-SQ	0.53	0.50
a(0)	-1.48	-0.82
a(1)	-0.28	0.44
a(2)	12.00	4.51
S.E.~	1.07	0.42

Ricker: $\ln(R/S)=a(0)+a(1)S+a(2)DT/T$
log-log: $\log(R)=a(0)+a(1)\log(S)+a(2)DT/T$

~S.E. is the standard error of the estimate on the multiple regression.

Table 3. Description of parameter sets for various SDP analyses.

PARAMETER SET	DESCRIPTION
1. Minimization of Variance Series for Numerical Harvest	
HR1L4	Desired harvest = 1 million fish/yr
HR2L4	Desired harvest = 3 million fish/yr
HR3L4	Desired harvest = 5 million fish/yr
HR4L4	Desired harvest = 10 million fish/yr
HR5L4	Desired harvest = 50 million fish/yr
SPMIN1	Desired harvest = 3 million fish/yr and effort interval =.05 per yr.
2. Maximization of Biomass	
WRML4	Desired biomass of harvest = 100 million kg/yr
3. Minimization of Variance Series for Fishable Stock	
F05E4	Desired Spring Fishable Stock = 5 million
F10E4	Desired Spring Fishable Stock = 10 million
F15E4	Desired Spring Fishable Stock = 15 million
4. Series for Variation in Maturity of 3-yr Old Fish	
HRM24	100% of 3-yr Olds Mature
HRM14	50% of 3-yr Olds Mature
HR5L4	19% of 3-yr Olds Mature

Table 4. Summary of optimal control for parameter set HR1L4. The upper portion indicates the frequency distribution of effort for various juvenile states (I1+I2-1). These data represent the absolute number of population states out of 1296 that are associated with a particular juvenile state and effort level (per year). The lower portion shows the quota that would be optimal for various combinations of adult and juvenile density (in millions). Densities are calculated from (Ii+Ij-2)*2 where Ii and Ij are the indices of the ages contributing to the computation.

	JUVENILE STATE										
EFFORT	1	2	3	4	5	6	7	8	9	10	11
0.00	21	40	63	93	118	158	129	116	86	64	31
0.15	13	27	38	44	55	51	48	27	22	8	5
0.30	1	4	4	4	4	5	3	1	0	0	0
0.45	1	0	1	2	1	1	0	0	0	0	0
0.60	0	0	1	0	1	0	0	0	0	0	0
0.75	0	0	0	0	0	0	0	0	0	0	0
0.90	0	0	0	0	0	0	0	0	0	0	0
1.05	0	0	0	0	0	0	0	0	0	0	0
1.20	0	0	0	0	0	0	0	0	0	0	0
1.35	0	0	0	0	0	0	0	0	0	0	0
1.50	0	0	0	0	1	0	0	0	0	0	0
1.65	0	0	0	0	0	0	0	0	0	0	0
1.80	0	0	0	0	0	1	0	0	0	0	0
1.95	0	0	0	0	0	0	0	0	0	0	0
2.10	0	0	0	1	0	0	0	0	0	0	0
2.25	0	0	0	0	0	0	0	0	0	0	0
2.40	0	0	0	0	0	0	0	0	0	0	0
2.55	0	0	1	0	0	0	0	0	0	0	0
2.70	0	0	0	0	0	0	0	0	0	0	0
2.85	0	0	0	0	0	0	0	0	0	0	0
3.00	0	1	0	0	0	0	0	0	0	0	0

JUVENILE	ADULT DENSITY										
DENSITY	0	2	4	6	8	10	12	14	16	18	20
0	0.0	0.5	0.6	0.0	1.0	0.0	1.5	0.0	0.0	0.0	0.0
2	0.2	0.4	0.4	0.9	0.0	1.4	0.0	1.1	0.0	0.0	0.0
4	0.5	0.7	0.8	0.0	1.3	0.0	1.5	0.0	0.0	0.0	0.0
6	0.6	0.5	0.2	1.2	0.0	1.4	0.0	0.2	0.0	0.0	0.0
8	0.7	0.7	1.1	0.0	1.3	0.0	0.9	0.0	0.0	0.0	0.0
10	0.5	0.6	0.2	1.2	0.1	1.0	0.0	0.1	0.0	0.0	0.0
12	0.9	0.7	1.3	0.0	1.1	0.0	0.6	0.0	0.0	0.0	0.0
14	0.3	0.6	0.0	1.3	0.1	0.7	0.0	0.0	0.0	0.0	0.0
16	1.1	0.7	1.6	0.0	0.9	0.0	0.0	0.0	0.0	0.0	0.0
18	0.0	0.7	0.0	1.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0
20	1.3	0.8	1.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 5. Summary of optimal control for parameter set HR2L4. The upper portion indicates the frequency distribution of effort for various juvenile states (I1+I2-1). These data represent the absolute number of population states out of 1296 that are associated with a particular juvenile state and effort level (per year). The lower portion shows the quota that would be optimal for various combinations of adult and juvenile density (in millions). Densities are calculated from (Ii+Ij-2)*2 where Ii and Ij are the indices of the ages contributing to the computation.

	JUVENILE STATE										
EFFORT	1	2	3	4	5	6	7	8	9	10	11
0.00	7	9	21	20	42	32	48	28	36	19	18
0.15	12	24	33	54	63	102	69	79	44	43	13
0.30	10	29	31	53	48	61	49	34	26	9	5
0.45	7	10	21	13	19	11	10	3	2	1	0
0.60	0	0	2	3	4	6	3	0	0	0	0
0.75	0	0	0	0	2	2	1	0	0	0	0
0.90	0	0	0	1	0	0	0	0	0	0	0
1.05	0	0	0	0	1	0	0	0	0	0	0
1.20	0	0	0	0	1	0	0	0	0	0	0
1.35	0	0	0	0	0	0	0	0	0	0	0
1.50	0	0	0	0	0	1	0	0	0	0	0
1.65	0	0	0	0	0	0	0	0	0	0	0
1.80	0	0	0	0	0	0	0	0	0	0	0
1.95	0	0	0	0	0	0	0	0	0	0	0
2.10	0	0	0	0	0	0	0	0	0	0	0
2.25	0	0	0	0	0	0	0	0	0	0	0
2.40	0	0	0	0	0	0	0	0	0	0	0
2.55	0	0	0	0	0	0	0	0	0	0	0
2.70	0	0	0	0	0	0	0	0	0	0	0
2.85	0	0	0	0	0	1	0	0	0	0	0
3.00	0	0	0	0	0	0	0	0	0	0	0

JUVENILE	ADULT DENSITY										
DENSITY	0	2	4	6	8	10	12	14	16	18	20
0	0.0	0.0	1.2	1.2	2.6	1.6	2.3	2.1	0.0	2.3	0.0
2	0.0	0.1	1.1	2.0	1.8	2.7	2.2	3.1	2.1	0.0	2.6
4	0.0	0.6	2.0	1.9	2.7	2.3	2.7	1.5	0.0	2.5	0.0
6	0.2	0.7	1.6	2.3	2.3	2.9	1.8	2.8	2.4	0.0	2.9
8	0.1	1.7	2.4	2.3	2.8	1.7	2.6	0.9	0.0	2.8	0.0
10	1.5	1.6	1.9	2.7	1.8	2.6	1.2	2.9	2.7	0.0	3.2
12	1.3	2.3	2.7	2.1	2.7	1.4	2.7	0.5	0.0	3.1	0.0
14	1.8	1.7	1.7	2.8	1.8	2.8	0.7	2.7	2.9	0.0	3.5
16	1.9	2.6	2.9	2.2	2.8	0.9	2.6	0.0	0.0	3.3	0.0
18	2.7	1.5	1.7	3.2	1.4	2.5	0.0	3.0	3.2	0.0	3.7
20	1.3	3.0	3.5	0.0	2.3	0.0	2.8	0.0	0.0	3.6	0.0

Table 6. Summary of optimal control for parameter set HR3L4. The upper portion indicates the frequency distribution of effort for various juvenile states (I1+I2-1). These data represent the absolute number of population states out of 1296 that are associated with a particular juvenile state and effort level (per year). The lower portion shows the quota that would be optimal for various combinations of adult and juvenile density (in millions). Densities are calculated from (Ii+Ij-2)*2 where Ii and Ij are the indices of the ages contributing to the computation.

	JUVENILE STATE										
EFFORT	1	2	3	4	5	6	7	8	9	10	11
0.00	7	10	17	18	22	25	19	17	11	12	4
0.15	4	7	12	16	33	32	51	24	41	13	18
0.30	7	27	18	51	30	78	34	64	20	37	7
0.45	12	20	42	42	60	51	52	30	29	10	7
0.60	6	8	17	13	28	15	20	9	7	0	0
0.75	0	0	2	4	2	10	3	0	0	0	0
0.90	0	0	0	0	3	2	1	0	0	0	0
1.05	0	0	0	0	2	1	0	0	0	0	0
1.20	0	0	0	0	0	1	0	0	0	0	0
1.35	0	0	0	0	0	0	0	0	0	0	0
1.50	0	0	0	0	0	0	0	0	0	0	0
1.65	0	0	0	0	0	0	0	0	0	0	0
1.80	0	0	0	0	0	0	0	0	0	0	0
1.95	0	0	0	0	0	0	0	0	0	0	0
2.10	0	0	0	0	0	0	0	0	0	0	0
2.25	0	0	0	0	0	0	0	0	0	0	0
2.40	0	0	0	0	0	0	0	0	0	0	0
2.55	0	0	0	0	0	0	0	0	0	0	0
2.70	0	0	0	0	0	0	0	0	0	0	0
2.85	0	0	0	0	0	0	0	0	0	0	0
3.00	0	0	0	0	0	1	0	0	0	0	0

JUVENILE	ADULT DENSITY										
DENSITY	0	2	4	6	8	10	12	14	16	18	20
0	0.0	0.0	0.9	0.8	2.6	4.1	3.3	4.3	3.7	0.0	0.0
2	0.0	0.0	0.9	2.3	2.3	3.4	4.4	3.9	2.7	2.4	2.6
4	0.0	0.1	1.9	2.6	3.5	4.3	4.1	4.3	2.9	0.0	0.0
6	0.0	0.5	1.8	3.1	3.1	4.1	4.8	3.9	1.4	2.7	2.9
8	0.2	1.0	2.9	3.8	4.3	4.0	3.7	4.3	2.9	0.4	0.0
10	0.4	1.9	2.8	3.7	3.4	4.3	4.8	3.3	0.9	3.1	3.2
12	0.7	2.4	3.6	4.3	4.6	3.8	3.3	3.9	2.8	0.0	0.0
14	2.0	2.6	3.2	4.0	3.5	4.6	5.0	2.8	0.0	3.2	3.5
16	1.4	3.6	4.2	4.8	4.9	3.4	2.7	3.2	3.1	0.0	0.0
18	3.2	3.2	3.2	4.2	3.5	4.9	4.3	1.4	0.0	3.5	3.7
20	2.5	4.2	4.9	4.7	4.0	2.6	2.3	3.1	3.4	0.0	0.0

Table 7. Summary of optimal control for parameter set HR4L4. The upper portion indicates the frequency distribution of effort for various juvenile states (I1+I2-1). These data represent the absolute number of population states out of 1296 that are associated with a particular juvenile state and effort level (per year). The lower portion shows the quota that would be optimal for various combinations of adult and juvenile density (in millions). Densities are calculated from (Ii+Ij-2)*2 where Ii and Ij are the indices of the ages contributing to the computation.

	JUVENILE STATE										
EFFORT	1	2	3	4	5	6	7	8	9	10	11
0.00	6	9	12	14	15	13	13	8	4	2	1
0.15	4	0	2	2	2	4	1	2	4	0	0
0.30	0	10	4	9	5	5	1	6	1	3	1
0.45	5	8	11	12	20	22	20	5	6	6	4
0.60	4	17	19	27	37	47	37	34	37	23	15
0.75	8	16	27	46	50	68	54	56	41	27	15
0.90	5	10	24	29	38	34	38	26	12	11	0
1.05	4	2	9	4	10	14	12	5	2	0	0
1.20	0	0	0	0	3	6	2	1	1	0	0
1.35	0	0	0	1	0	1	1	0	0	0	0
1.50	0	0	0	0	0	0	0	1	0	0	0
1.65	0	0	0	0	0	0	0	0	0	0	0
1.80	0	0	0	0	0	0	0	0	0	0	0
1.95	0	0	0	0	0	0	0	0	0	0	0
2.10	0	0	0	0	0	0	0	0	0	0	0
2.25	0	0	0	0	0	0	0	0	0	0	0
2.40	0	0	0	0	0	0	1	0	0	0	0
2.55	0	0	0	0	0	0	0	0	0	0	0
2.70	0	0	0	0	0	0	0	0	0	0	0
2.85	0	0	0	0	0	0	0	0	0	0	0
3.00	0	0	0	0	0	2	0	0	0	0	0

JUVENILE	ADULT DENSITY										
DENSITY	0	2	4	6	8	10	12	14	16	18	20
0	0.0	0.0	0.0	0.8	2.6	4.5	6.4	7.3	9.5	8.6	8.2
2	0.0	0.0	1.0	2.0	2.8	4.4	6.3	8.0	8.5	9.0	10.8
4	0.0	0.0	1.4	3.0	4.3	5.6	7.4	8.2	9.4	10.8	6.3
6	0.0	0.1	1.8	4.0	5.0	6.2	7.3	8.9	9.3	8.9	5.5
8	0.0	0.6	2.8	4.7	5.8	6.6	8.2	8.6	9.1	10.5	4.4
10	0.0	1.7	3.5	5.6	6.4	7.3	8.2	9.2	10.0	9.6	3.7
12	0.2	1.8	4.8	6.1	7.1	7.5	8.9	9.7	9.5	11.2	2.5
14	0.3	3.1	5.0	6.8	7.6	8.2	9.5	9.8	10.9	10.0	0.0
16	1.4	3.1	5.6	6.8	8.0	8.3	9.8	11.1	9.6	10.9	0.0
18	2.7	4.7	5.9	8.1	8.1	9.0	9.9	10.2	11.8	10.1	0.0
20	3.5	4.6	6.4	7.5	8.8	9.3	9.7	11.0	9.5	11.8	0.0

Table 8. Summary of optimal control for parameter set HR5L4. The upper portion indicates the frequency distribution of effort for various juvenile states (I1+I2-1). These data represent the absolute number of population states out of 1296 that are associated with a particular juvenile state and effort level (per year). The lower portion shows the quota that would be optimal for various combinations of adult and juvenile density (in millions). Densities are calculated from (Ii+Ij-2)*2 where Ii and Ij are the indices of the ages contributing to the computation.

	JUVENILE STATE										
EFFORT	1	2	3	4	5	6	7	8	9	10	11
0.00	6	20	16	19	17	18	14	10	7	4	2
0.15	5	0	8	4	1	4	1	1	1	0	0
0.30	0	10	3	15	8	13	6	3	1	2	0
0.45	5	10	18	8	17	8	7	6	3	2	1
0.60	6	3	6	23	21	8	18	4	5	2	1
0.75	4	1	23	18	33	30	24	14	11	3	3
0.90	4	14	16	16	35	38	30	24	16	14	3
1.05	3	12	3	30	20	41	31	23	27	6	12
1.20	2	2	12	10	14	39	20	35	18	18	3
1.35	1	0	3	1	12	14	25	17	11	15	5
1.50	0	0	0	0	2	3	2	5	6	3	5
1.65	0	0	0	0	0	0	2	2	2	3	1
1.80	0	0	0	0	0	0	0	0	0	0	0
1.95	0	0	0	0	0	0	0	0	0	0	0
2.10	0	0	0	0	0	0	0	0	0	0	0
2.25	0	0	0	0	0	0	0	0	0	0	0
2.40	0	0	0	0	0	0	0	0	0	0	0
2.55	0	0	0	0	0	0	0	0	0	0	0
2.70	0	0	0	0	0	0	0	0	0	0	0
2.85	0	0	0	0	0	0	0	0	0	0	0
3.00	0	0	0	0	0	0	0	0	0	0	0

JUVENILE	ADULT DENSITY										
DENSITY	0	2	4	6	8	10	12	14	16	18	20
0	0.0	0.0	0.0	0.8	2.6	3.6	5.6	7.6	9.5	11.5	13.6
2	0.0	0.0	0.0	0.0	2.1	3.8	6.8	9.0	9.3	11.4	13.5
4	0.0	0.0	0.5	1.5	3.3	5.6	7.1	8.8	11.4	13.0	15.1
6	0.0	0.0	1.3	2.3	4.1	5.9	8.0	10.3	12.0	12.9	15.0
8	0.0	0.0	2.1	4.1	5.8	7.2	8.7	10.0	12.5	14.7	16.7
10	0.0	0.4	2.5	5.3	6.7	8.6	10.3	11.7	13.5	15.8	16.4
12	0.0	0.4	3.3	5.8	8.1	9.7	10.8	11.8	13.6	16.1	18.2
14	0.0	1.1	4.2	6.7	8.9	10.7	12.3	13.7	15.2	17.4	17.8
16	0.0	1.3	5.5	7.5	9.7	11.6	12.9	14.0	15.0	17.2	20.1
18	0.0	1.9	6.5	8.9	10.7	12.5	13.9	15.3	16.6	19.1	19.8
20	0.0	3.1	7.6	9.6	11.6	13.4	14.8	15.7	16.1	18.6	22.3

Table 9. Summary of optimal control for parameter set WRML4. The upper portion indicates the frequency distribution of effort for various juvenile states (I1+I2-1). These data represent the absolute number of population states out of 1296 that are associated with a particular juvenile state and effort level (per year). The lower portion shows the quota that would be optimal for various combinations of adult and juvenile density (in millions). Densities are calculated from (Ii+Ij-2)*2 where Ii and Ij are the indices of the ages contributing to the computation.

	JUVENILE STATE										
EFFORT	1	2	3	4	5	6	7	8	9	10	11
0.00	8	16	22	23	19	22	17	11	9	5	3
0.15	4	4	5	5	5	2	2	3	0	1	0
0.30	2	6	9	18	5	20	3	6	1	2	0
0.45	4	12	15	11	21	7	13	4	5	0	2
0.60	5	5	14	3	41	10	22	6	5	2	1
0.75	3	5	7	32	24	45	20	21	10	6	0
0.90	4	11	16	15	27	34	37	21	22	12	4
1.05	3	11	6	26	16	36	28	24	21	16	9
1.20	2	2	11	11	11	28	22	28	21	12	9
1.35	1	0	3	0	10	11	15	17	9	12	4
1.50	0	0	0	0	1	1	1	3	5	4	2
1.65	0	0	0	0	0	0	0	0	0	0	2
1.80	0	0	0	0	0	0	0	0	0	0	0
1.95	0	0	0	0	0	0	0	0	0	0	0
2.10	0	0	0	0	0	0	0	0	0	0	0
2.25	0	0	0	0	0	0	0	0	0	0	0
2.40	0	0	0	0	0	0	0	0	0	0	0
2.55	0	0	0	0	0	0	0	0	0	0	0
2.70	0	0	0	0	0	0	0	0	0	0	0
2.85	0	0	0	0	0	0	0	0	0	0	0
3.00	0	0	0	0	0	0	0	0	0	0	0

JUVENILE	ADULT DENSITY										
DENSITY	0	2	4	6	8	10	12	14	16	18	20
0	0.0	0.0	0.0	0.4	2.0	3.5	5.2	7.6	9.5	11.5	13.6
2	0.0	0.0	0.0	0.4	2.5	3.9	6.6	8.8	9.3	11.4	13.5
4	0.0	0.0	0.0	1.0	3.0	4.7	7.0	8.9	11.3	13.0	15.1
6	0.0	0.0	0.8	1.8	3.3	6.4	7.9	10.1	12.0	12.7	15.0
8	0.0	0.0	1.9	3.4	5.1	6.1	8.4	10.2	12.4	14.7	16.7
10	0.0	0.0	2.0	4.7	6.1	8.1	9.5	11.4	13.6	15.8	16.4
12	0.0	0.0	3.0	5.5	7.5	8.8	10.5	11.6	13.6	16.0	18.2
14	0.0	0.2	3.4	6.3	8.4	10.4	11.8	13.3	15.2	17.6	17.8
16	0.0	0.0	4.9	7.2	9.8	11.3	12.8	13.3	15.0	17.2	20.4
18	0.0	0.4	5.7	8.0	10.3	12.5	13.5	15.3	16.4	19.1	20.4
20	0.0	0.0	6.5	9.1	11.6	13.6	15.0	15.8	16.9	18.6	22.3

Table 10. Summary of optimal control for parameter set F05E4. The upper portion indicates the frequency distribution of effort for various juvenile states (I1+I2-1). These data represent the absolute number of population states out of 1296 that are associated with a particular juvenile state and effort level (per year). The lower portion shows the quota that would be optimal for various combinations of adult and juvenile density (in millions). Densities are calculated from (Ii+Ij-2)*2 where Ii and Ij are the indices of the ages contributing to the computation.

	JUVENILE STATE										
EFFORT	1	2	3	4	5	6	7	8	9	10	11
0.00	10	12	11	11	6	2	0	0	0	0	0
0.15	3	8	2	1	2	3	1	0	0	0	0
0.20	2	0	4	2	6	3	1	0	0	0	0
0.45	6	10	10	10	4	3	1	0	0	0	0
0.60	5	8	10	5	8	3	3	2	0	0	0
0.75	6	9	17	15	2	10	3	1	1	0	0
0.90	3	9	17	25	18	13	6	1	0	0	0
1.05	1	10	15	15	29	10	10	3	0	0	0
1.20	0	5	13	21	24	31	14	5	2	0	0
1.35	0	1	7	16	18	30	18	13	2	1	0
1.50	0	0	2	11	15	19	25	12	3	0	0
1.65	0	0	0	6	16	14	14	16	10	1	0
1.80	0	0	0	3	12	11	16	14	11	0	0
1.95	0	0	0	3	10	11	8	12	8	1	0
2.10	0	0	0	0	4	10	9	7	8	0	0
2.25	0	0	0	0	4	2	8	8	7	10	0
2.40	0	0	0	0	2	4	3	8	11	8	1
2.55	0	0	0	0	0	2	4	5	4	6	0
2.70	0	0	0	0	0	0	1	2	5	8	0
2.85	0	0	0	0	0	1	0	0	1	2	0
3.00	0	0	0	0	0	34	35	35	35	35	35

JUVENILE	ADULT DENSITY										
DENSITY	0	2	4	6	8	10	12	14	16	18	20
0	0.0	0.0	0.0	0.0	1.4	3.3	4.9	6.7	8.7	8.6	11.9
2	0.0	0.0	0.0	0.9	3.0	4.8	6.7	8.6	10.4	11.8	13.9
4	0.0	0.0	1.1	2.8	4.6	6.3	8.1	9.8	11.0	13.2	15.4
6	0.0	0.1	2.3	4.4	6.3	8.0	9.5	11.0	13.3	14.7	16.2
8	0.0	1.5	3.4	5.7	7.8	9.5	11.4	13.1	14.4	16.3	18.3
10	0.7	3.2	5.5	7.4	9.4	11.2	13.0	14.8	16.5	18.1	19.8
12	1.9	5.1	7.1	9.0	10.8	12.6	14.6	16.3	18.0	19.8	21.4
14	3.9	6.7	9.0	10.8	12.6	14.2	16.1	17.9	19.6	21.5	23.1
16	5.6	8.5	10.6	12.6	14.4	16.1	17.8	19.5	21.2	22.9	24.8
18	7.7	10.5	12.5	14.5	16.2	18.1	19.8	21.5	23.1	24.7	26.3
20	9.8	12.3	14.1	15.9	17.7	19.5	21.3	23.1	24.9	26.7	28.5

Table 11. Summary of optimal control for parameter set F10E4. The upper portion indicates the frequency distribution of effort for various juvenile states (I1+I2-1). These data represent the absolute number of population states out of 1296 that are associated with a particular juvenile state and effort level (per year). The lower portion shows the quota that would be optimal for various combinations of adult and juvenile density (in millions). Densities are calculated from (Ii+Ij-2)*2 where Ii and Ij are the indices of the ages contributing to the computation.

	JUVENILE STATE										
EFFORT	1	2	3	4	5	6	7	8	9	10	11
0.00	36	55	59	54	31	23	12	4	2	0	0
0.15	0	17	24	31	27	13	4	4	1	0	0
0.30	0	0	21	25	26	20	7	4	2	3	0
0.45	0	0	4	20	29	37	19	8	3	0	1
0.60	0	0	0	9	29	31	24	11	6	1	0
0.75	0	0	0	4	16	35	34	17	9	4	1
0.90	0	0	0	1	13	27	28	27	14	4	2
1.05	0	0	0	0	6	16	27	29	17	8	1
1.20	0	0	0	0	3	10	16	21	24	12	6
1.35	0	0	0	0	0	4	9	12	18	21	8
1.50	0	0	0	0	0	0	0	7	9	12	7
1.65	0	0	0	0	0	0	0	0	3	7	8
1.80	0	0	0	0	0	0	0	0	0	0	2
1.95	0	0	0	0	0	0	0	0	0	0	0
2.10	0	0	0	0	0	0	0	0	0	0	0
2.25	0	0	0	0	0	0	0	0	0	0	0
2.40	0	0	0	0	0	0	0	0	0	0	0
2.55	0	0	0	0	0	0	0	0	0	0	0
2.70	0	0	0	0	0	0	0	0	0	0	0
2.85	0	0	0	0	0	0	0	0	0	0	0
3.00	0	0	0	0	0	0	0	0	0	0	0

JUVENILE	ADULT DENSITY										
DENSITY	0	2	4	6	8	10	12	14	16	18	20
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0	0.0	0.0	1.6	0.0	0.7	1.8	2.6
4	0.0	0.0	0.0	0.0	0.0	1.5	3.1	0.8	1.5	4.7	5.8
6	0.0	0.0	0.0	0.0	1.4	3.1	4.7	3.8	2.5	3.6	7.1
8	0.0	0.0	0.0	1.3	3.2	4.5	6.5	8.0	9.0	8.7	9.0
10	0.0	0.0	1.0	3.0	4.5	6.3	8.3	9.5	11.8	13.5	13.2
12	0.0	0.4	2.9	4.6	6.5	8.1	10.1	11.6	13.3	15.2	16.7
14	0.0	1.8	4.0	6.5	8.3	9.9	11.8	13.4	15.2	16.8	18.9
16	0.3	3.3	5.7	7.4	9.9	11.8	13.6	15.2	16.7	18.6	19.6
18	2.3	4.8	7.5	9.4	11.3	13.5	15.4	17.1	18.6	20.3	22.0
20	3.5	6.6	9.1	11.1	12.9	14.4	16.8	18.6	20.6	22.2	23.3

Table 12. Summary of optimal control for parameter set F15E4. The upper portion indicates the frequency distribution of effort for various juvenile states (I1+I2-1). These data represent the absolute number of population states out of 1296 that are associated with a particular juvenile state and effort level (per year). The lower portion shows the quota that would be optimal for various combinations of adult and juvenile density (in millions). Densities are calculated from (Ii+Ij-2)*2 where Ii and Ij are the indices of the ages contributing to the computation.

	JUVENILE STATE										
EFFORT	1	2	3	4	5	6	7	8	9	10	11
0.00	36	72	108	135	155	161	129	74	43	20	8
0.15	0	0	0	9	15	18	32	25	25	11	6
0.30	0	0	0	0	9	26	12	17	15	15	1
0.45	0	0	0	0	1	11	4	14	10	10	6
0.60	0	0	0	0	0	0	3	13	12	6	8
0.75	0	0	0	0	0	0	0	1	2	6	3
0.90	0	0	0	0	0	0	0	0	1	4	3
1.05	0	0	0	0	0	0	0	0	0	0	1
1.20	0	0	0	0	0	0	0	0	0	0	0
1.35	0	0	0	0	0	0	0	0	0	0	0
1.50	0	0	0	0	0	0	0	0	0	0	0
1.65	0	0	0	0	0	0	0	0	0	0	0
1.80	0	0	0	0	0	0	0	0	0	0	0
1.95	0	0	0	0	0	0	0	0	0	0	0
2.10	0	0	0	0	0	0	0	0	0	0	0
2.25	0	0	0	0	0	0	0	0	0	0	0
2.40	0	0	0	0	0	0	0	0	0	0	0
2.55	0	0	0	0	0	0	0	0	0	0	0
2.70	0	0	0	0	0	0	0	0	0	0	0
2.85	0	0	0	0	0	0	0	0	0	0	0
3.00	0	0	0	0	0	0	0	0	0	0	0

JUVENILE	ADULT DENSITY										
DENSITY	0	2	4	6	8	10	12	14	16	18	20
0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0	0.0	0.5	1.7	0.0	0.0	0.0	0.7
10	0.0	0.0	0.0	0.0	0.2	1.7	2.2	0.6	1.0	1.6	1.2
12	0.0	0.0	0.0	0.0	0.8	1.6	2.0	0.1	1.1	0.7	1.5
14	0.0	0.0	0.0	1.4	2.9	3.5	2.5	2.2	2.2	2.5	1.8
16	0.0	0.0	1.1	3.4	4.0	4.4	2.0	2.1	2.4	2.7	3.6
18	0.0	0.0	2.7	3.5	6.5	4.5	4.5	3.5	6.0	6.5	8.3
20	0.0	0.8	4.4	6.6	7.7	5.9	7.5	3.7	3.4	9.5	10.1

Table 13. Summary of optimal control for parameter set HRM24. The upper portion indicates the frequency distribution of effort for various juvenile states (I1+I2-1). These data represent the absolute number of population states out of 1296 that are associated with a particular juvenile state and effort level (per year). The lower portion shows the quota that would be optimal for various combinations of adult and juvenile density (in millions). Densities are calculated from (Ii+Ij-2)*2 where Ii and Ij are the indices of the ages contributing to the computation.

	JUVENILE STATE										
EFFORT	1	2	3	4	5	6	7	8	9	10	11
0.00	6	20	9	7	7	6	5	1	1	0	0
0.15	4	0	4	5	0	1	0	1	0	0	0
0.30	0	10	7	18	2	8	0	3	0	1	0
0.45	5	6	20	3	13	0	4	0	1	0	0
0.60	6	0	17	15	6	24	2	0	1	0	1
0.75	0	16	6	30	30	21	8	3	4	1	0
0.90	8	8	15	37	35	33	34	8	7	0	0
1.05	4	7	15	14	41	24	46	14	9	2	0
1.20	2	5	12	7	41	37	21	40	20	17	15
1.35	1	0	3	8	5	54	24	40	33	15	7
1.50	0	0	0	0	0	4	29	12	15	14	0
1.65	0	0	0	0	0	0	4	18	11	15	4
1.80	0	0	0	0	0	0	0	1	3	4	6
1.95	0	0	0	0	0	0	0	0	0	0	0
2.10	0	0	0	0	0	0	0	0	0	0	0
2.25	0	0	0	0	0	0	0	0	0	0	0
2.40	0	0	0	0	0	0	0	0	0	0	0
2.55	0	0	0	0	0	0	0	0	0	0	0
2.70	0	0	0	0	0	0	0	0	0	0	0
2.85	0	0	0	0	0	0	0	0	0	0	0
3.00	0	0	0	0	0	4	3	3	3	3	3

JUVENILE	ADULT DENSITY										
DENSITY	0	2	4	6	8	10	12	14	16	18	20
0	0.0	0.0	0.0	0.8	2.6	4.1	6.5	8.3	8.7	11.5	13.6
2	0.0	0.0	0.0	0.0	2.1	4.6	6.3	8.2	10.6	11.4	13.5
4	0.0	0.0	1.8	2.0	3.7	5.2	7.7	9.6	11.4	13.0	15.1
6	0.2	0.4	1.8	4.0	4.9	6.7	7.9	9.4	11.7	14.5	15.0
8	0.6	1.5	3.6	5.1	6.3	8.3	9.4	11.3	12.9	14.4	16.7
10	1.4	2.6	5.6	6.0	7.4	9.0	10.5	12.6	14.3	16.1	17.8
12	1.2	3.5	7.1	6.8	8.3	10.5	11.8	13.9	15.6	17.2	19.1
14	1.9	4.9	8.7	8.4	9.9	11.6	13.5	15.2	17.1	18.5	20.6
16	2.4	6.8	9.9	8.6	10.0	12.6	14.2	16.4	17.9	20.1	21.9
18	3.6	7.4	12.0	10.6	11.9	13.2	15.8	17.6	19.5	21.0	22.9
20	4.4	8.9	14.1	10.9	12.2	13.5	15.8	18.8	21.1	22.7	24.2

Table 14. Summary of optimal control for parameter set HRM14. The upper portion indicates the frequency distribution of effort for various juvenile states (I1+I2-1). These data represent the absolute number of population states out of 1296 that are associated with a particular juvenile state and effort level (per year). The lower portion shows the quota that would be optimal for various combinations of adult and juvenile density (in millions). Densities are calculated from (Ii+Ij-2)*2 where Ii and Ij are the indices of the ages contributing to the computation.

	JUVENILE STATE										
EFFORT	1	2	3	4	5	6	7	8	9	10	11
0.00	6	20	15	12	12	12	8	6	2	1	0
0.15	4	0	2	1	2	2	2	1	2	1	1
0.30	0	10	6	12	4	9	1	5	1	2	0
0.45	5	12	17	8	15	1	7	1	1	1	1
0.60	6	0	5	24	3	22	3	2	4	1	0
0.75	3	4	27	21	42	20	24	4	5	1	3
0.90	5	14	9	35	27	51	22	19	2	4	0
1.05	4	8	11	20	40	37	33	34	17	2	2
1.20	2	4	13	6	22	39	52	30	33	17	6
1.35	1	0	3	5	13	23	19	32	22	24	8
1.50	0	0	0	0	0	0	5	5	14	12	10
1.65	0	0	0	0	0	0	0	0	0	1	0
1.80	0	0	0	0	0	0	1	0	0	0	0
1.95	0	0	0	0	0	0	0	0	0	0	0
2.10	0	0	0	0	0	0	0	0	0	0	0
2.25	0	0	0	0	0	0	0	1	0	0	0
2.40	0	0	0	0	0	0	0	0	0	0	0
2.55	0	0	0	0	0	0	0	0	1	0	1
2.70	0	0	0	0	0	0	0	0	0	1	0
2.85	0	0	0	0	0	0	0	0	0	0	1
3.00	0	0	0	0	0	0	3	4	4	4	3

JUVENILE	ADULT DENSITY										
DENSITY	0	2	4	6	8	10	12	14	16	18	20
0	0.0	0.0	0.0	0.8	2.6	4.1	6.1	8.1	9.0	11.5	13.6
2	0.0	0.0	0.0	0.0	2.1	3.6	6.8	8.4	10.1	11.4	13.5
4	0.0	0.0	0.9	2.1	3.7	5.9	7.2	9.4	11.5	13.0	15.1
6	0.0	0.1	1.8	3.9	5.0	6.1	7.9	9.6	11.6	13.5	15.0
8	0.0	0.6	2.6	5.2	6.6	7.7	8.7	10.8	13.0	15.0	16.7
10	0.2	1.1	3.7	5.7	7.3	9.2	10.4	11.6	13.3	15.4	16.4
12	0.0	1.9	5.4	7.0	8.7	10.0	11.0	12.6	14.7	16.6	19.0
14	0.6	1.7	6.6	8.4	9.6	11.2	12.6	13.8	15.1	17.6	18.9
16	0.4	3.7	8.2	9.6	10.8	12.1	13.6	15.2	16.9	18.1	20.7
18	1.2	3.3	10.0	11.3	12.0	13.3	14.8	16.4	17.4	20.1	20.4
20	1.3	5.2	11.8	12.9	12.8	13.9	16.1	18.0	19.1	19.8	22.3

Table 15. Summary of simulations of SDP strategies for 1000-yr periods. DAta are presented by the parameter set names listed in Table 3.

MODEL PARAMETER SET	ANNUAL HARVEST (MILLIONS)		SPRING ADULT DENSITY (MILLIONS)		OPTMAL EFFORT (PER YR)	
	MEAN	S.D.	MEAN	S.D.	MEAN	S.D.
HR1L4	0.63	0.33	8.46	3.54	0.06	0.03
HR2L4	2.28	0.63	4.90	3.29	0.30	0.12
HR3L4	3.09	1.37	3.33	2.61	0.44	0.17
HR4L4	3.35	1.89	2.29	0.82	0.55	0.30
HR5L4	3.40	2.62	2.87	0.65	0.45	0.24
SPMIN1	2.54	0.58	4.43	2.92	0.33	0.11
WRML4	3.55	2.75	3.14	0.65	0.44	0.26
F05E4	2.94	2.80	1.96	1.23	0.76	0.89
F10E4	2.93	2.59	4.15	1.52	0.36	0.33
F15E4	0.89	1.42	7.79	1.83	0.08	0.13
HRM24	3.68	2.77	3.29	1.44	0.71	0.54
HRM14	3.53	2.95	2.93	1.18	0.64	0.61

Table 16. Summary of 1000-yr simulations of various constant effort strategies using eith a Ricker or a log-log stock-recruitment relationship.

S-R RELATIONSHIP	EFFORT (PER YR)	HARVEST (MILLIONS)		ADULTS (MILLIONS)	
		MEAN	S.D.	MEAN	S.D.
Ricker	0.4	3.16	1.46	3.41	1.49
Ricker	0.5	3.16	1.63	2.40	1.15
log-log	0.2	1.67	0.69	4.73	1.90

Table 17. Quota recommendations derived from various exploitation strategies. The constant effort strategies are for Ricker (CES-1) and log-log (CES-2) stock-recruitment relationships. The SDP strategies are based on objectives to maximize numerical harvest (SDP-1) and to maximize biomass of harvest (SDP-2). Estimates of the state of the stock (by density of ages I, II, III, and IV+) were for 1980: 7.2, 0.9, 12.9, and 3.5; and for 1981: 19.4, 5,7, 0.6, and 10.8 million fish in the spring of the year.

	1980		1981	
STRATEGY	OPTIMAL EFFORT (PER YR)	QUOTA (MILLIONS)	OPTIMAL EFFORT (PER YR)	QUOTA (MILLIONS)
CES-1	0.40	5.30	0.40	5.60
CES-2	0.20	2.90	0.20	3.00
SDP-1	1.09	11.00	0.67	8.30
SDP-2	1.02	10.50	0.70	8.60

FIGURE LEGENDS

Fig. 1. Observed stock-recruitment data compared with predicted by a Ricker relationship (solid line) and by a log-log relationship (dotted line) assuming a DT/T of 0.215 deg C/day.

Fig. 2. The trade-off or pareto frontier for mean annual harvest versus S.D. of harvest for 1000-yr simulations. The solid line represents the results of the minimization of variance series in Table 3, the [Δ] represents the change in the frontier caused by a finer control interval (SPMIN1 in Table 3), and [⊡] represents the results for constant effort of 0.4 per year. All simulations used a Ricker stock-recruitment relationship.

Fig. 3. Quota recommendations for various combinations of adult and juvenile densities for parameter set SPMIN1.

Fig. 4. Quota recommendations for various combinations of adult and juvenile densities for parameter set HR2L4.

Fig. 5. Yield versus effort curves for various versions of Ricker stock-recruitment relationship. The dashed line is a fully stochastic version; the dotted line is the result of only DT/T varying; and the solid line is the deterministic result.

Fig. 6. Yield versus effort curves for various version of a log-log stock-recruitment relationship. The dashed line is a fully stochastic version; the dotted line is the result of only DT/T varying; and the solid line is the determinitic result.

Fig. 7. Linear transformation of the fitted Ricker stock-recruitment relationship (eq. 1) and observed data from Table 1.

Fig. 8. Linear transformation of the fitted log-log stock-recruitment relationship (eq. 2) and the observed data from Table 1.

Fig. 9. Harvest versus effort predictions from a deterministic model of a walleye population with a Ricker stock-recruitment relationship. The dotted line is for the estimated parameters in Table 2 and a DT/T of 0.215/yr; and the solid line and dashed lines are for a(1) values - 2 S.E. and + 2 S.E. respectively.

Fig. 10. Stock-recruitment curves used in the deterministic simulations for Fig. 9. Solid line is a(1) - 2 S.E., dotted line is a(1) estimated in Table 2, and the dashed line is a(1) + 2 S.E.

Fig. 11. Harvest versus effort curves for various maturity

and catchability schedules. The solid line is standard catchability schedule, for ages I to IV+, (0.0653,1,1,1) and standard maturity, for ages I to IV+, (0,0,0.19,1); the dotted line is standard catchability, but earlier maturity (0,0,1,1); and the dashed line is both earlier maturity (0,0,1,1) and delayed catchability (0.0.5,1,1).

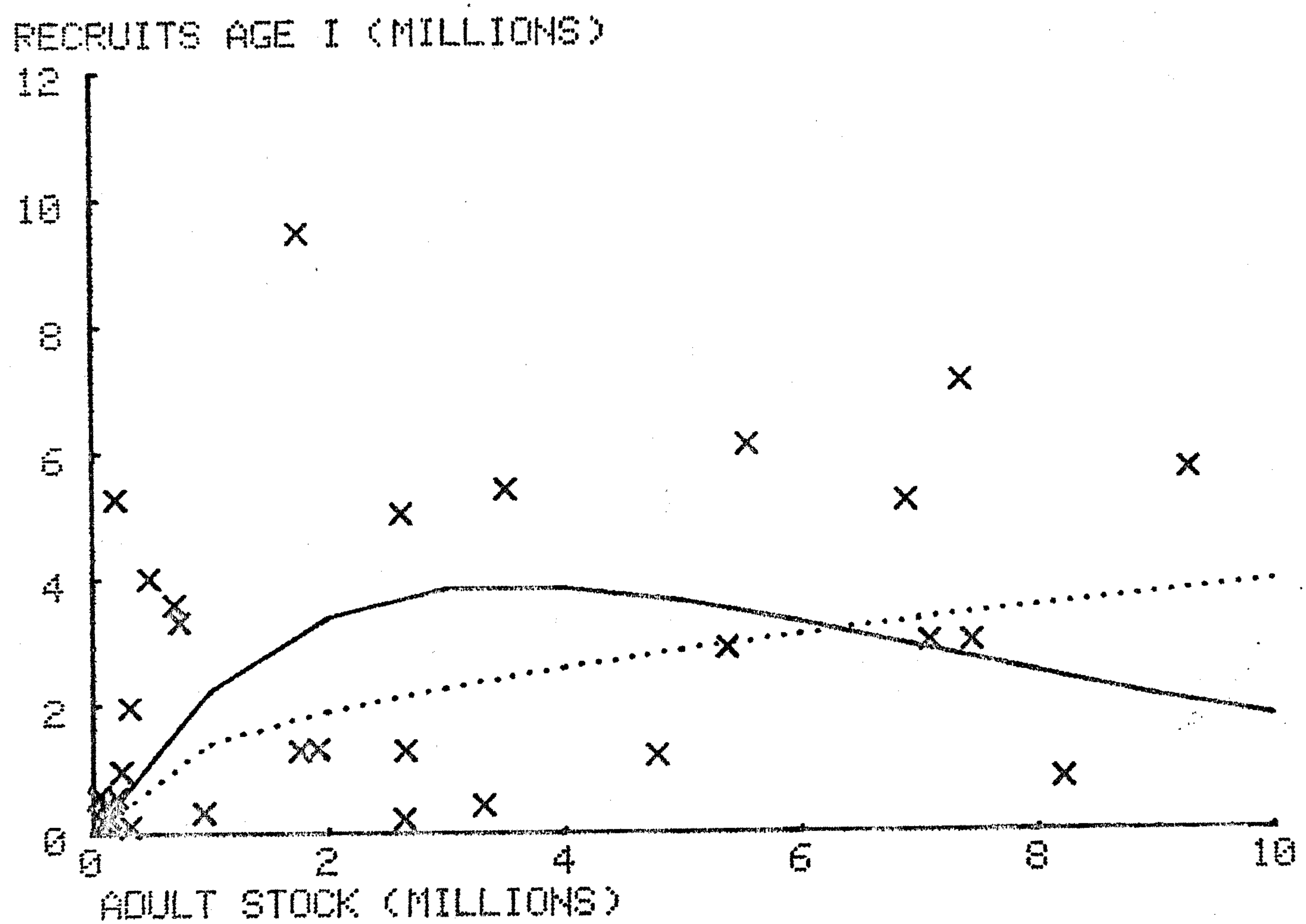

RECRUITS AGE I (MILLIONS)
12
10
8
6
4
2
0
0
2
4
6
8
10
ADULT STOCK (MILLIONS)

FIG. 1

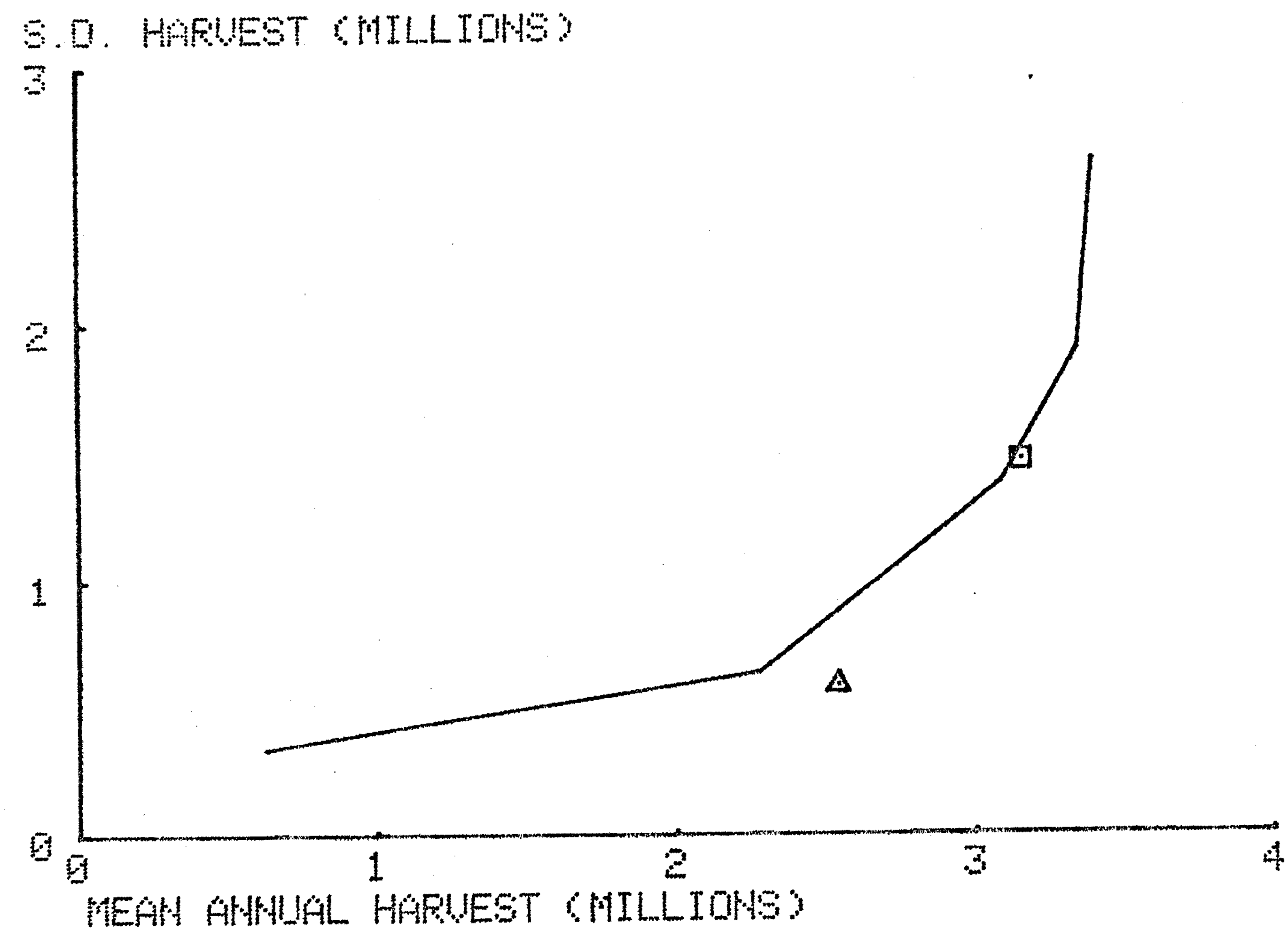

S.D. HARVEST (MILLIONS)
3
2
1
0
0
1
2
3
4
MEAN ANNUAL HARVEST (MILLIONS)

FIG. 2

Fig. 3

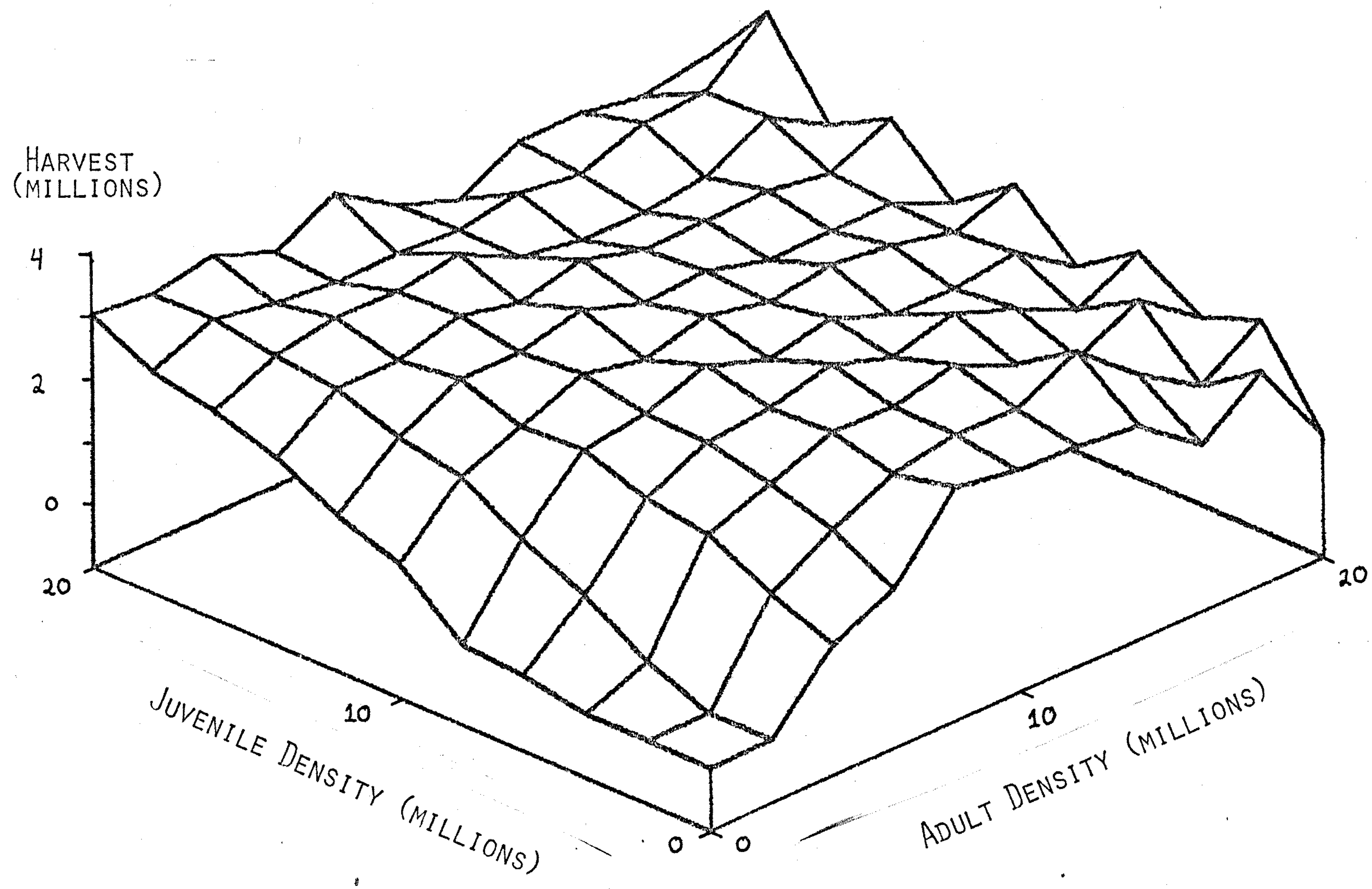
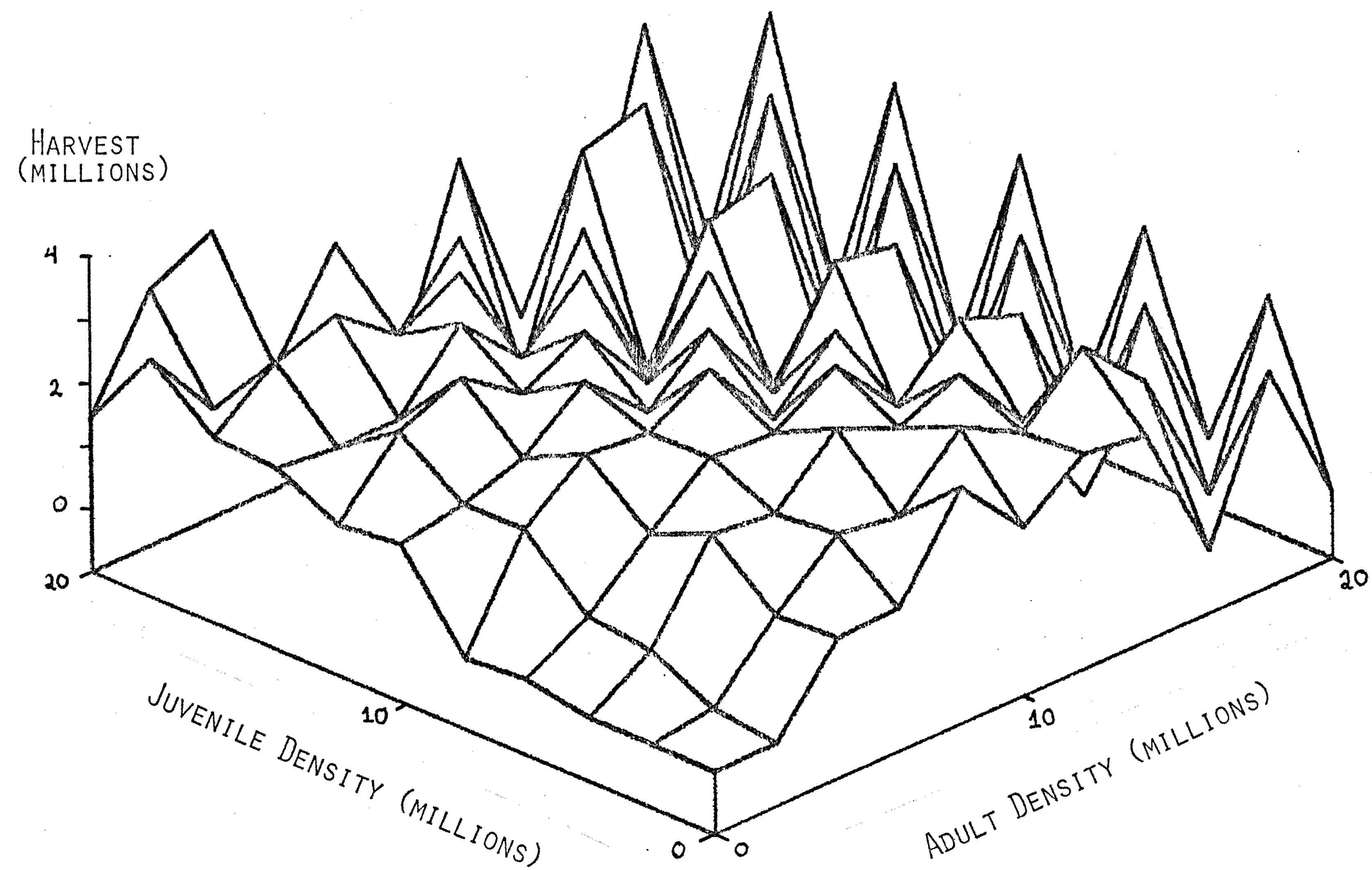

HARVEST
(MILLIONS)
4
2
0
20
10
0
JUVENILE DENSITY (MILLIONS)
0
10
20
ADULT DENSITY (MILLIONS)

Fig. 4


HARVEST
(MILLIONS)
4
2
0
20
10
0
JUVENILE DENSITY (MILLIONS)
0
10
20
ADULT DENSITY (MILLIONS)

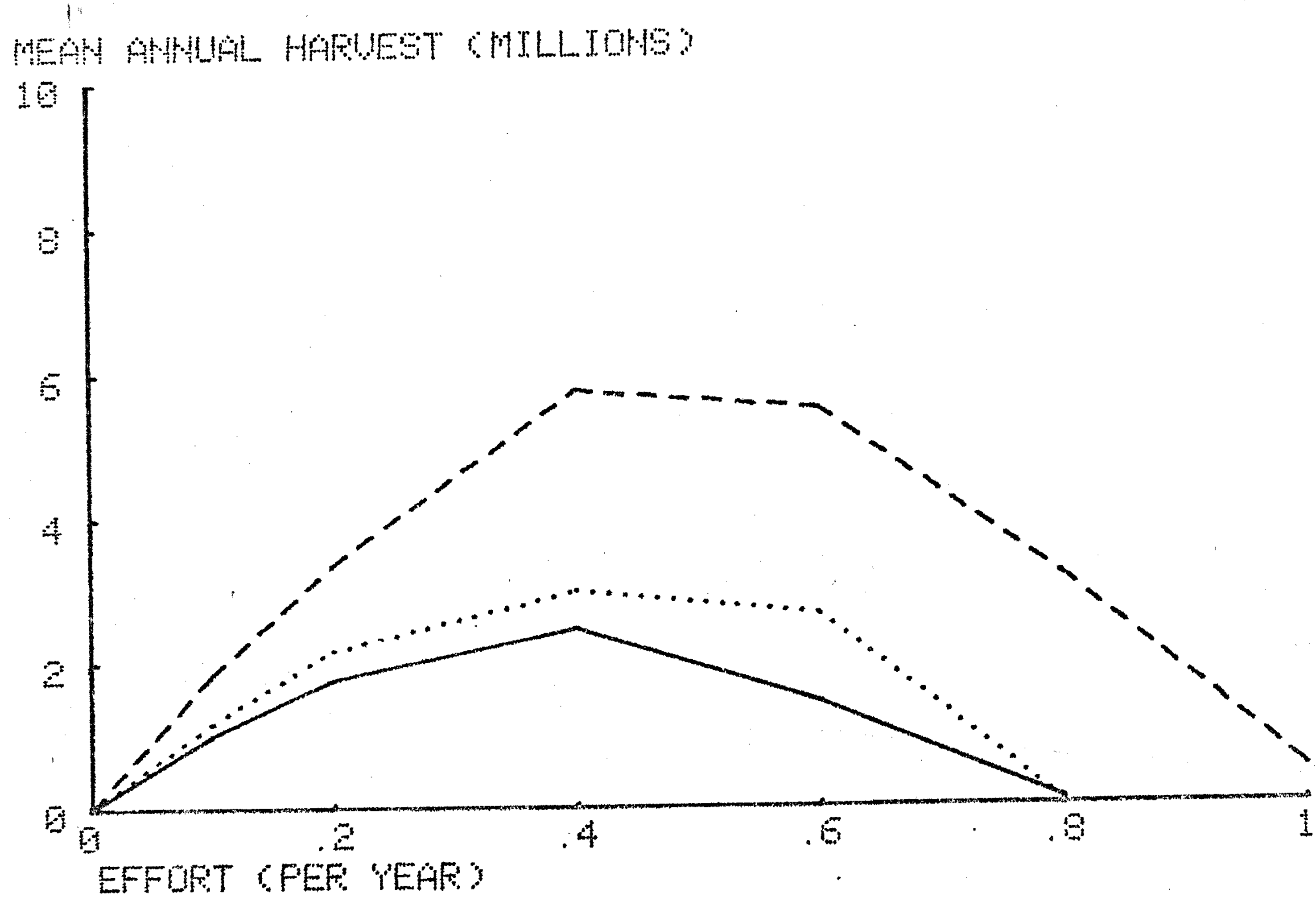

MEAN ANNUAL HARVEST (MILLIONS)
10
8
6
4
2
0
0
.2
.4
.6
.8
1
EFFORT (PER YEAR)

FIG. 5

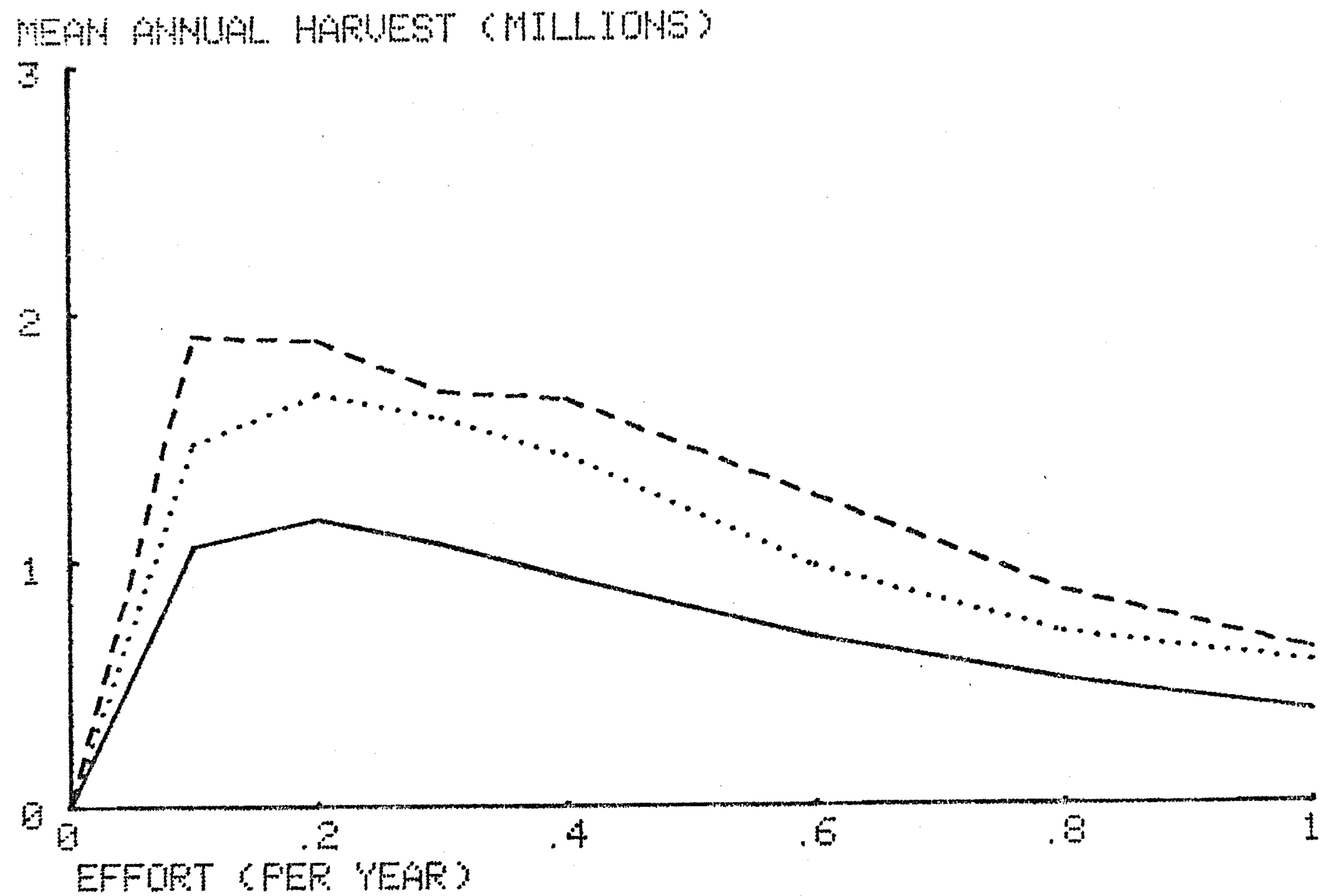


FIG. 6

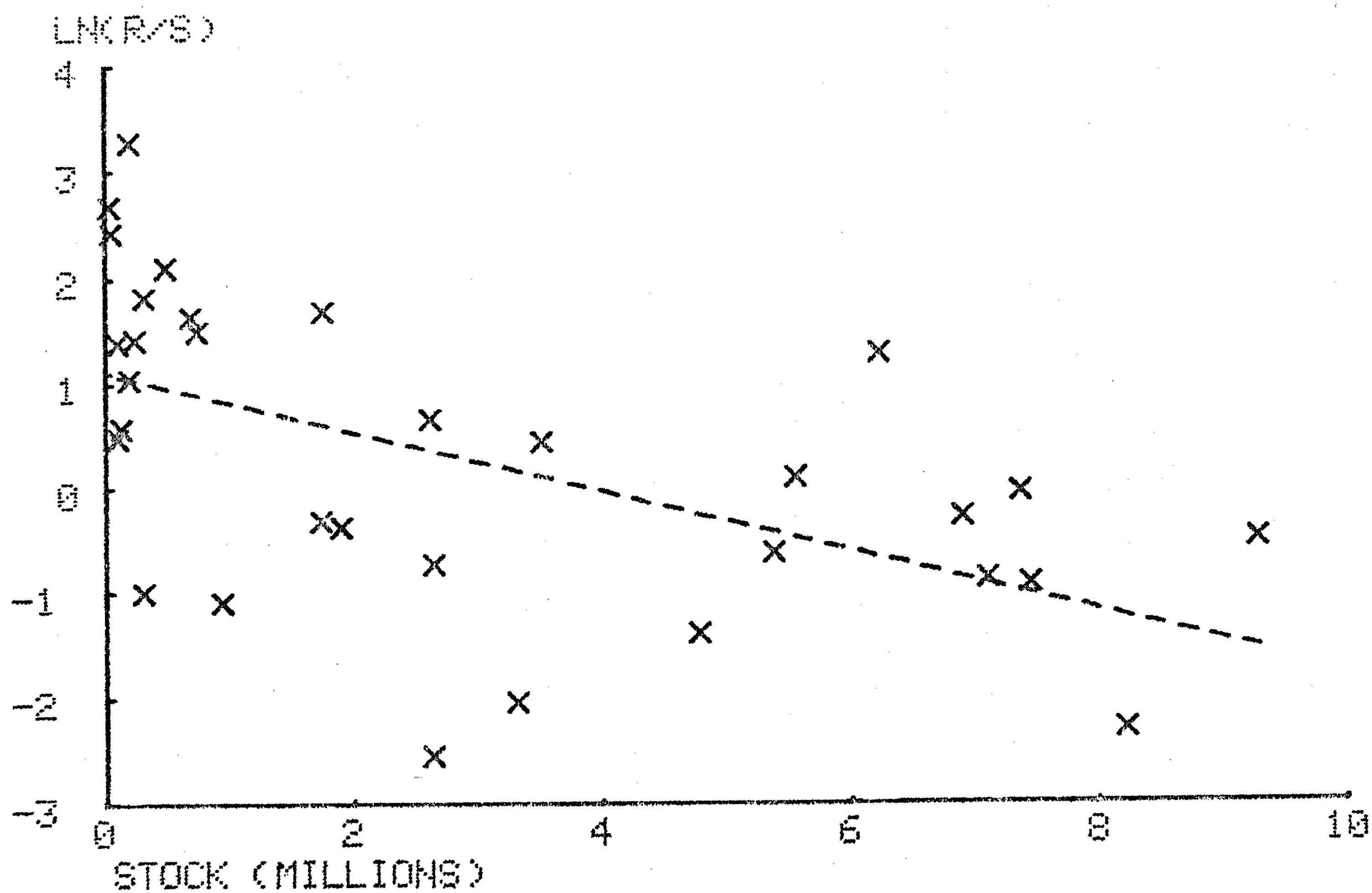


FIG. 7

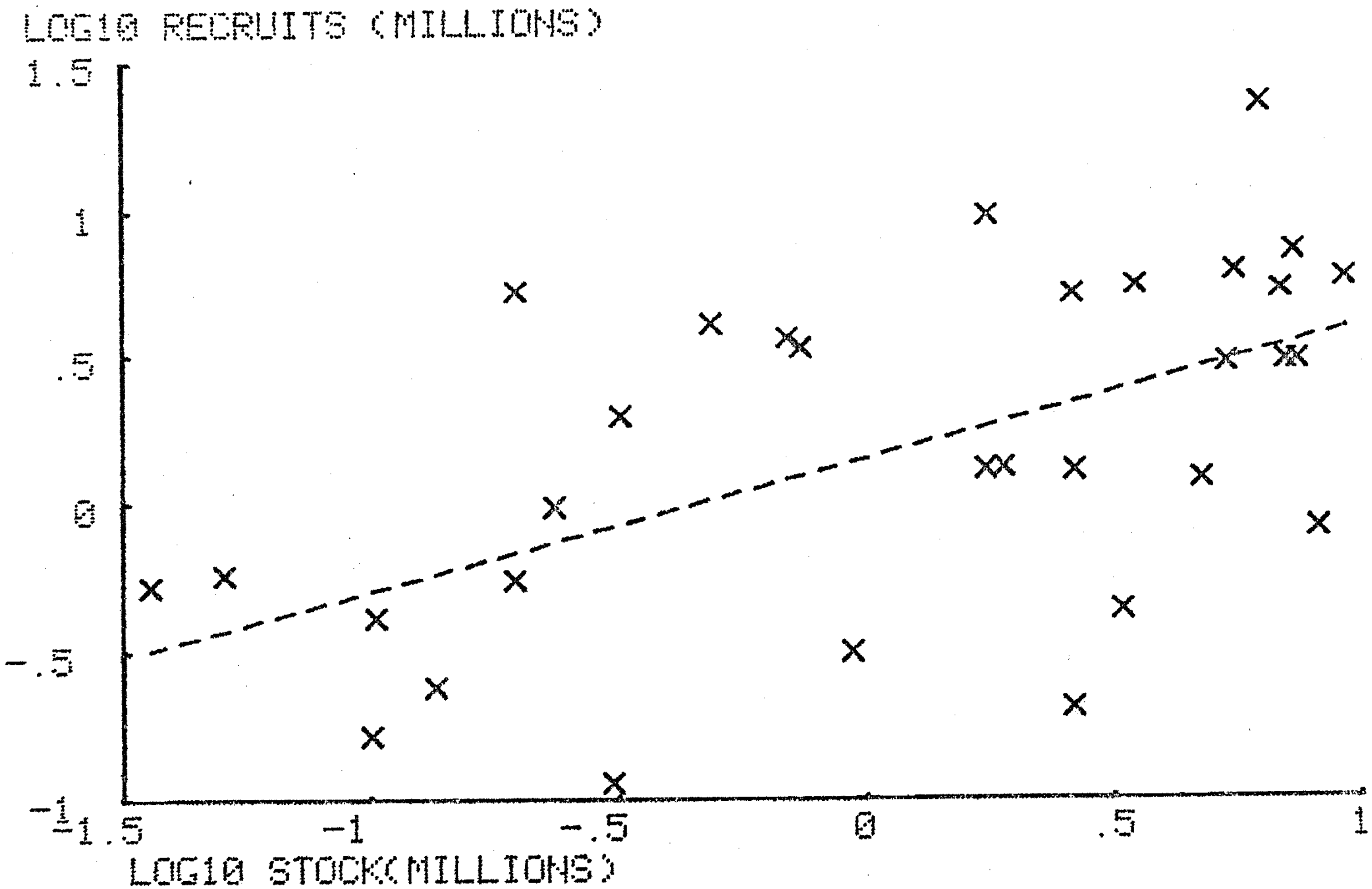

LOG10 RECRUITS (MILLIONS)
1.5
1
.5
0
-.5
-1
-1.5
-1
-.5
0
.5
1
LOG10 STOCK(MILLIONS)

FIG 8

Fig. 9

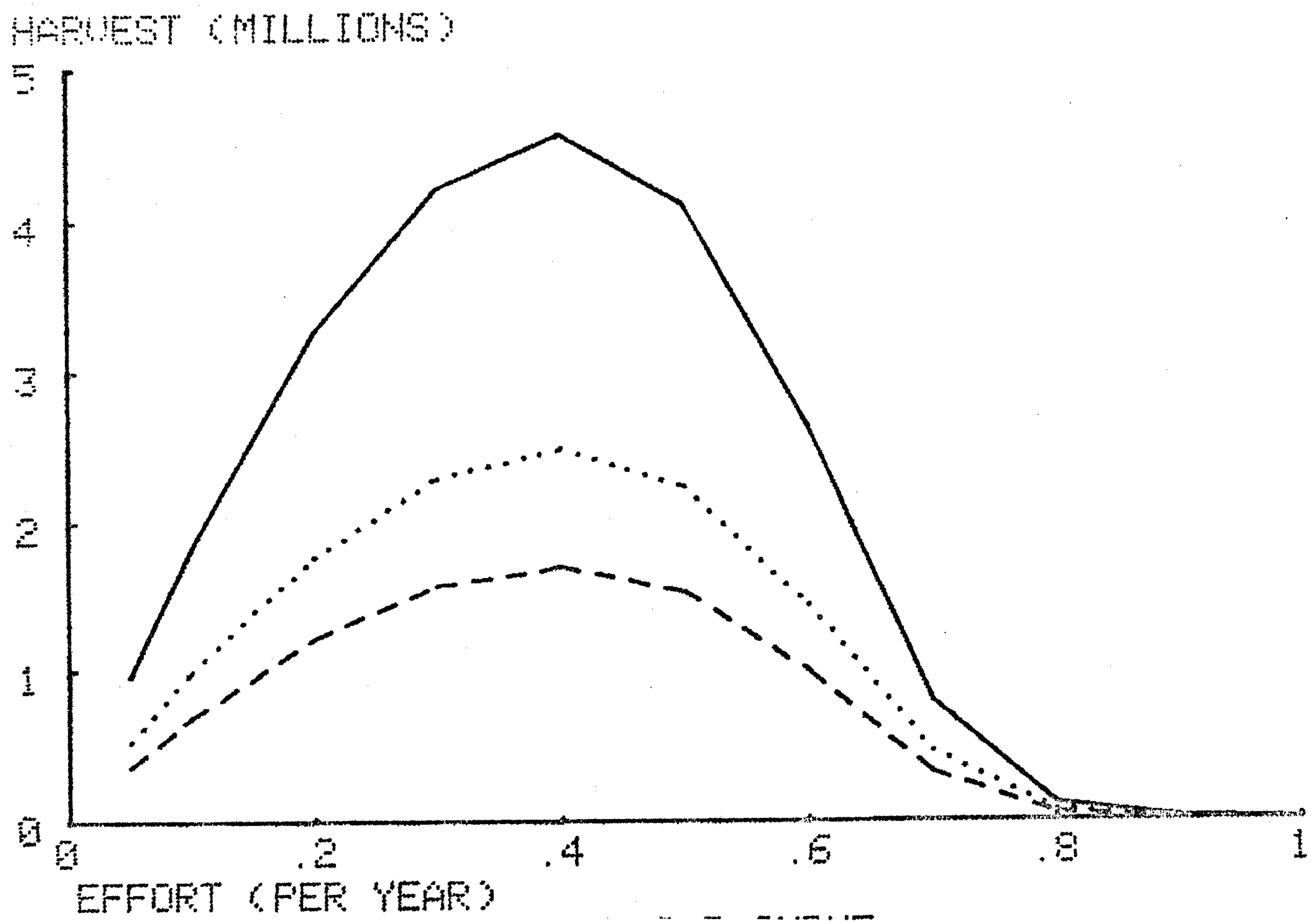
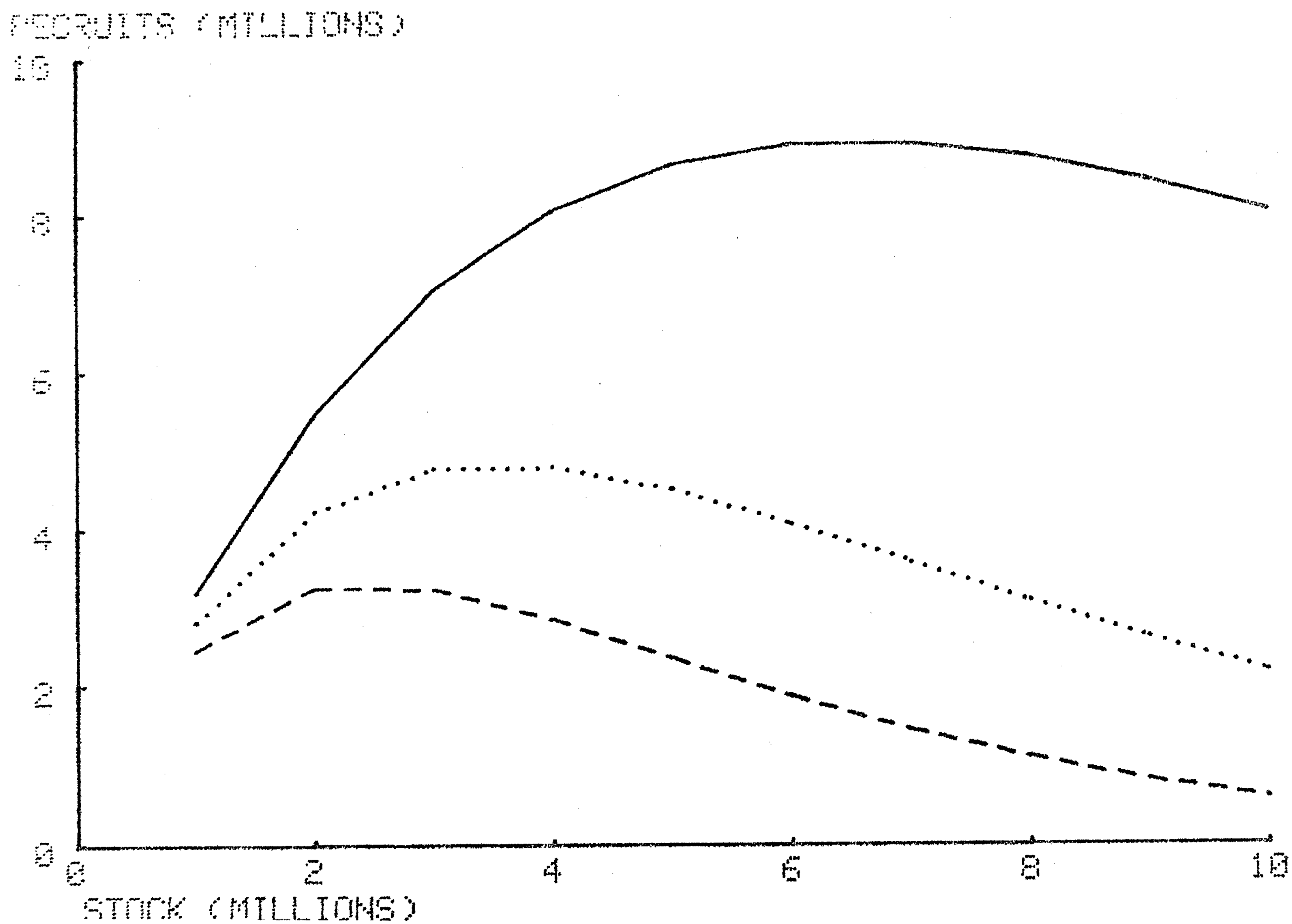


Fig. 10



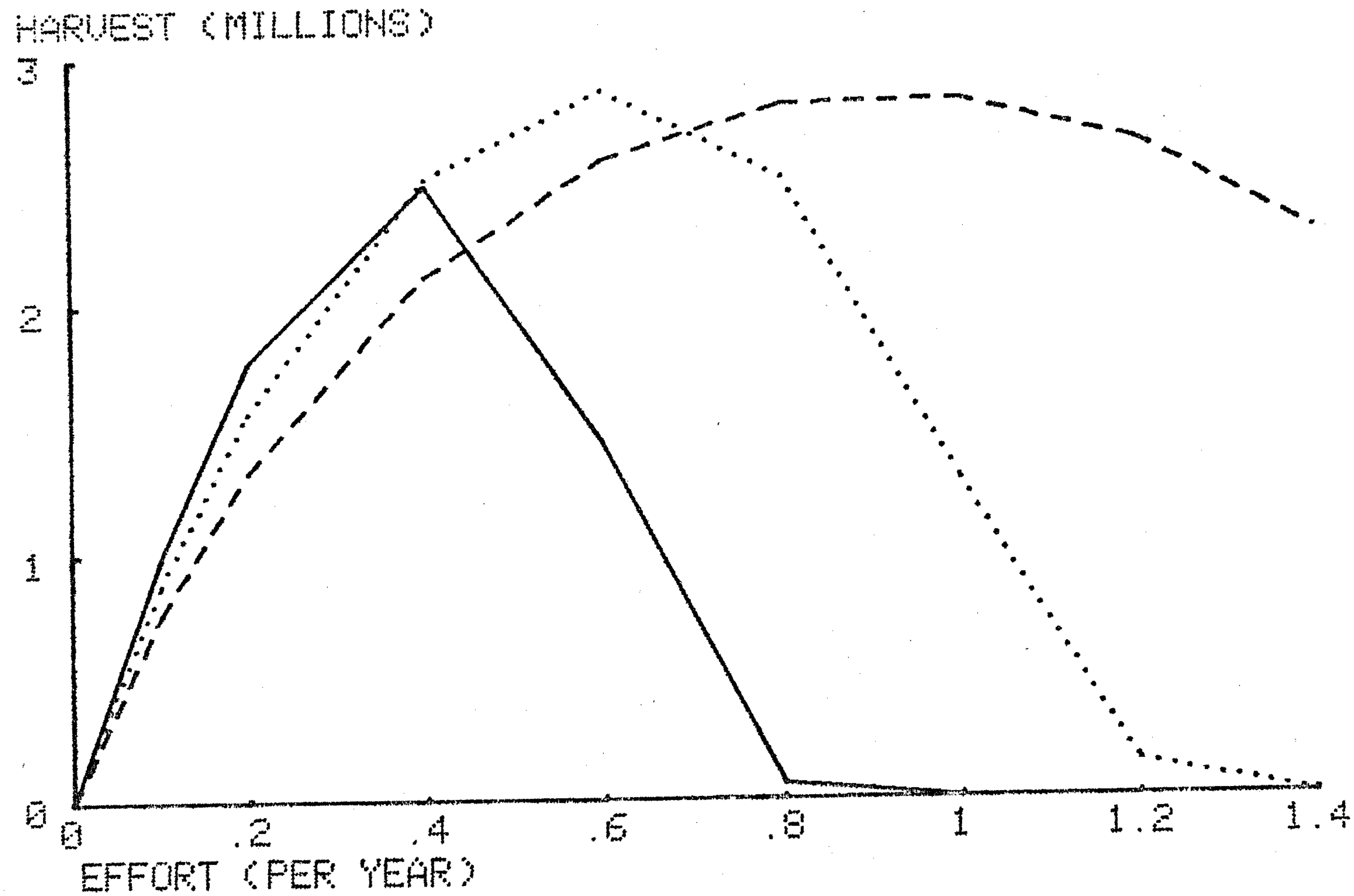


FIG. 11