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Evaluation of Optimal Strategies for Harvesting Walleye in Western Lake Erie

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INTRODUCTION

The walleye population of Western Lake Erie has been an important recreational and commercial resource since the early part of this century (Regier et al. 1969; Parsons 1970; and Nepszy 1977). Exploitation of this fishery reached non-sustainable levels in the mid-1950's, and overexploitation may have contributed to the population decline discussed by many authors (Regier et al. 1969; Parsons 1970; Hartman 1973; Busch et al. 1975; and Nepszy 1977). In 1969, the commercial fishery was closed because of mercury contamination, and it remained closed until 1976 when limited commercial fishing resumed in Ontario waters. Available data (Kutkuhn et al. 1976) indicated that walleye stocks recovered in the period 1969-1978. Within the framework of the Great Lakes Fisheries Commission, the Standing Technical Committee for Lake Erie recommended quotas for commercial and recreation catch (Standing Technical Committee 1978).

Supplementing the on going quota deliberations for Walleye catch in Western Lake Erie, the Great Lakes Fisheries Commission authorized a feasibility study of modelling this population (Shuter and Koonce 1977; and Shuter et al. 1979). This feasibility study examined the data base available for this population, developed a quantitative model of the population, and explored possible ways of using dynamic models to manage the population. The work reported here was an attempt to examine more fully some of the management implications of the known sources of variability in the population regulation of walleye in Western Lake Erie.

Standard methods of setting quotas for the management of specific fish stocks (Clark 1976; Ricker 1975) are often based on a set of deterministic relationships assumed to characterize those processes that determine the overall productivity of the stock (e.g. growth, recruitment, and natural mortality). The variability in such relationships that is caused by environmental randomness is often ignored. Recent work by a number of authors (Beddington and May 1977; Walters 1975; Walters and Hilborn 1976) has shown that inclusion of random variability in stock-production relationships can lead to management strategies considerably different from those derived from strictly deterministic relationships. In general, these studies emphasized that maximization of average yield and minimization of year to year variations in yield can be mutually exclusive objectives. They also emphasized the necessity of deciding on some "optimal" balance between magnitude and stability of yield as a pre-requisite to the formulation of an explicit management strategy (i.e. a procedure for calculating allowable harvest from current stock status) for a particular stock. Formal methods for deriving such strategies have appeared in the recent literature (Anderson 1975; Walters 1975; and Walters and Hilborn 1976). Such methods are also useful to assess the value of research/monitoring programs aimed at providing better quantitative information of the processes governing stock productivity (Huang, Vertinsky and Wilimovsky 1976).

In extending our earlier work, our objectives were two-fold: 1) To use mathematical models to define optimal strategies for the exploitation of a single, age-structured population whose population regulation is subject to stochastic variation; and 2) To evaluate the benefits arising from research/monitoring programs that would identify the nature of the variability underlying population regulation.

DATA ANALYSIS

Much of our data analysis was an extension of our earlier work (Shuter and Koonce 1977; and Shuter et al. 1979). The purpose of additional analyses was to test and refine a stock-recruitment relationship for the period 1947-1978. In these analyses we continued to explore the importance of the spring temperature regime (Busch et al. 1975) and the adult stock on recruitment. Our index of recruitment was an estimate of the number of individuals in each year class at the start (spring) of their third year of life (aged II). We obtained these estimates for the period 1947-69 from Shuter et al. (1979) and for the period 1970-78 from the reports of the Lake Erie

Standing Technical Committee (1978).

We estimated reproductive potential in two ways. One index of reproductive potential we used was based on the number of eggs laid. We derived this estimate as follows: 1) We estimated the number of fish aged III and over in the spring of each year from the data sources cited above. 2) We estimated the biomass of mature fish from the numerical density data and data on age of maturity, growth rate, and length-weight relationships cited in Shuter et al. (1979). 3) Finally, we calculated the number of eggs laid each year from the mature biomass by assuming 82.6 eggs/g of mature female biomass (Wolfert 1969) and a 1:1 sex ratio. The second index of reproductive potential was the number of fish that may have been mature in the spring of each year (item 1 above). We assumed a minimum age of maturity for females to be 3 years (Wolfert 1969). The rate of water temperature increase (deg C/day) in the spring was calculated as in Shuter et al. (1979). These data are summarized in Table 1.

The reason for using two indices of reproductive potential related to our uncertainty about the effect of density dependent growth rates on our models. The shape of a stock recruitment relationship based on eggs laid is not sensitive to changes in growth rate and age of maturity due to effects of stock density. These stock effects are included in the calculation of numbers of eggs laid. However, the shape of a stock-recruitment curve based on numbers of mature adults does reflect changes in growth rate and age of maturity, which may be a function of stock size. We then examined four possible stock-recruitment relationships by fitting them with least squares procedure to the data for 1947-67:

$$\ln(R/S) = a_o + a_s S + a_T \Delta T/t \qquad (1)$$

$$\ln(R) = a_o + a_s \ln(S) + a_T \Delta T/t \qquad (2)$$

$$\ln(R) = a_o + a_T \Delta T/t \qquad (3)$$

$$\ln(R) = a_o + a_T \ln(\Delta T/t) \qquad (4)$$

where a_o , a_s , and a_T are fitted coefficients, R is the recruitment, S is the index of reproductive potential, $\Delta T/t$ is the rate of spring warming, and ln is the symbol of the natural logrithm. We compared these different relationships by correlating observed and predicted recruitment (Table 2). Equation 1 is a logrithmic transformation of a Ricker-type stock-recruitment relationship and equation 2 is a stock-recruitment relationship of the type applied to this walleye population by Shuter and Koonce (1977).

Correlations for the stock-recruitment relationships which include reproductive potential (i.e. Eqs. 1 and 2) have much higher coefficients of determination. In most cases, however, over half of the variation between predicted and observed recruitment is unexplained by stock and temperature alone. We further tested the parameters of Eqs. 1 to 4 with data from the period 1968-78 (Table 3). The relationships incorporating reproductive potential still seem superior, and the Ricker equation (Eq. 1) accounts for more variability than a Shuter-Koonce equation (eq. 2). Whether the egg density or adult density is a better index of reproductive potential is less clear. Ricker curves based on either index of reproductive potential explain more variability than any other relationship.

The Ricker curve provided a better fit to the data than the Shuter-Koonce curve primarily because of a low recruitment in 1978 when reproductive potential was quite high. Ricker curves fitted to the entire 1947-78 time series yield

	Index of Reproductive Potential	
	Eggs	Age III +
r	0.7153	0.723
R^2	0.5116	0.529
a_o	-5.321	-1.481
a_S	-0.00754	-0.2839
a_T	12.53	11.99
n	31	31

where the index of reproductive potential is either 1 billion eggs or 1 million fish aged 3 and over in the spring. Recruitment is then in units of 1 million fish starting their third year of life (age II). These relationships assuming aΔT/t of 0.225 are summarized in Fig. 1. The convex curvature in the Ricker type curves indicated that a density dependent effect other than reduced fecundity may occur in this population. Based on other evidence (Forney 1976), we would expect high adult densities to depress reproductive recruitment. Because the Shuter-Koonce relationship predicts an unlimited increase in recruitment with increasing stock density, we felt it was biologically less realistic, and given the apparent potential generality of a Ricker type curve, we chose to focus most of our attention on it. Predicted and observed recruitment of spring 2-yr olds are compared in Fig. 2.

The correlations obtained for these stock-recruitment relationships may reflect causal relationships. However, these results could also be an artifact of similar secular trends in reproductive potential and recruitment. We have discussed this problem elsewhere (Shuter et al. 1979), but we believe that two lines of evidence support a causal interpretation of the correlation results. First, the stock-recruitment relationships (Eqs. 1 and 2), whose parameters are fitted to 1947-67 data, predict 1968-78 recruitment reasonably well (Table 3). Second, we can divide the time series at 1964, which had the lowest value of reproductive potential, and fit Eqs. 1 and 2 to both time series. Results of this analysis are given in Table 4. The coefficients of determination are similar enough to weaken the secular trend objection to a causal interpretation.

These analyses suggest that a stock-recruitment relationship exists for walleye in Western Lake Erie. Reproductive potential and temperature effects suggested in earlier work (Busch et al. 1975; and Shuter et al. 1979) are confirmed by longer time series analysis. However, the stock-recruitment relationships leave nearly half of the variability in recruitment unexplained. This observation is based on the fact that the coefficient of determination is the ratio of explained to unexplained variance. To see if we could associate more of the variability with additional factors, we performed a stepwise multiple correlation for the data in Table 5 and the recruitment, reproductive potential (age III + fish only), and rate of spring water temperature increase from Table 1. The period covered in the analysis was 1947-68, excluding 1948. We obtained the meterological data from the U. S. Department of Commerce, U. S. Weather Bureau's Local Climatological Summary for Toledo, Ohio. Significant wave heights were calculated for the fetch, which we determined from the location of spawning reef areas and wind direction, and wind speed using a nomograph prepared by the U. S. Army (in Great Lakes Basin Commission 1976, p. 93). Finally, as a crude estimate of perch abundance, we used perch harvest data summarized by Nepszy (1977).

This multiple correlation analysis did not indicate any additonal factors that could substantially increase the explained variance (Table 6). The maximum ratio of explained to unexplained variance was 0.779, but did not substantially change from the value for reproductive potential and temperature change alone. Mean monthly water temperature, however, is not as informative as rates of change, and thus mean monthly precipitation or wave height may not be as significant as an index of change of these variables. Unfortunately, we did not have daily summaries for these variables. Although perch harvest also was not a significant variable in the analysis, its F value to remove may suggest some influence. A better measure of perch density might be pursued in future work. A causal relationship should be expected based on experience with other walleye populations (Forney 1976). In fact, there seems to be a significant negative correlation (r=-0.632, n=22) between abundance of walleye individuals age III and over and the harvest of yellow perch.

Our concern with sources of variability in recruitment to this population is important. In the analysis of management strategies that follow, we assume that the rate of temperature increase in spring is the principle stochastic variable affecting the population. Other analyses (Koonce et al. 1977) have indicated that effects of temperature on this population are not causally associated with the physiology of the walleye. Before the management strategies can be used with confidence, therefore, origins of the variability of recruitment need more careful examination--perhaps along the lines we have suggested.

EVALUATION OF OPTIMAL MANAGEMENT STRATEGIES

Model Development

The basic objective of the management of a fisheries resource is to maximize the sustainable value of the fishery. Traditionally, the concept of a maximum sustainable yield has been the guiding principle. The theoretical support for this concept is based on deterministic models. As discussed above, strategies recommended by these approaches may conflict with optimal strategies derived from a consideration of real variability in mortality and/or recruitment. In our earlier study (Shuter et al. 1979), we examined dynamic models of the walleye population for long term management strategies. The strategies focused on long term constant effort or individual cohort management. We also applied the principles of stochastic dynamic programming (Walters 1975) to this problem, but the analysis was limited to individual cohorts. Although all approaches indicated that low efforts seemed to be the best long-term strategy (Shuter and Koonce 1977), the stochastic dynamic programming approach indicated that an optimal strategy would require different efforts for different cohort densities. This finding was interesting because it suggested that one might be able to extract greater harvest by using information on the annual state of the stock.

To pursue the possibility of developing a strategy requiring annual quota setting required a different model than any reported earlier (Shuter and Koonce 1977). The stochastic dynamic programming (SDP) model had to be modified to apply to an age-structured population with overlapping generations. This model is documented and listed in Appendix A. The main change from our cohort model was the inclusion of four contemporary age groups (Ages I, II, III, and IV and over in the spring). Each of the age groups was subdivided into six densities. This structure resulted in 1296 possible states of the population (i.e. combinations of six density states for each of the four age groups). The density of each age group was

$$N_j = (I_j - 1)d_j \qquad (5)$$

where I_j is the state index of the jth age group and d_j is the absolute density interval defined as the maximum density divided by 5. We next defined an arbitrary population state index:

$$i = I_1 + \sum_{j=2}^{4} (I_j - 1)6^{(j-1)} \qquad (6)$$

This index had a value range of 1 to 1296.

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 i. 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. We included in our algorithm a possible discounting of future value. Unlike Walters (1975), we could not always obtain a stable control law without it. 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

$$H_t = \sum_{j=1}^{4} [U_i q_j / (U_i q_j + m_j)] N_{j,t-1} \; [1 - \exp(-U_i q_j - m_j)] \quad (7)$$

where m is the natural mortality for age group j and N is the density of age group j at time t-1. Recruitment to the yearling age group was given by the stock-recruitment relationships discussed above and the adult density defined as

$$S_t = \sum_{j=1}^{4} k_j N_{j,t} \qquad (8)$$

We explored the implications of each control law given by the SDP model. The primary analysis was a 100-year simulation of a population experiencing a randomly varying temperature regime. The model formulation was

$$N_{1,t+1} = f(S_t, \Delta T/t), \tag{9}$$

where S was defined in eq. 8, $\Delta T/t$ was a random variable, ~N(0.215,0.0048), and f was a recruitment function defined by either eq. 1 or 2. The equations for the remaining age groups were

$$N_{j+1,t+1} = N_{j,t} \exp(-U_i q_j - m_j), \; j=1,2 \tag{10}$$

and

$$N_{4,t+1} = \sum_{j=3}^{4} N_{j,t} \exp(-U_i q_j - m_j) \; . \tag{11}$$

Because its five dimensional character precluded a direct visual representation, we summarized the control law in two graphical formats. First, we summarized in a three dimensional graph the frequency of efforts associated with particular juvenile states $(\hat{I}_1 + \hat{I}_2)$. These frequency distributions primarily reflected the effect of various adult densities on optimal exploitation strategies. Using this feature, our other graphical summary was a three-dimensional representation of mean harvest (or quota) associated with various juvenile and adult densities.

Analysis Protocol

We performed SDP analysis on several versions of the model. These versions differed in the bype of stock-recruitment relationship and the type of objective function. For this report, however, we limit our comments to a version in which we assumed a Ricker type stock-recruitment relationship and an objective function that would allow us to minimize variance about specified harvest levels. As Walters (1975) indicated, this approach allowed for exploration of optimal strategies for either minimizing variance about attainable catches or maximizing catch simply by changing the desired harvest parameter. This version of the model is included as Appendix A.

The parameter set required for the model allowed a wide range of possible assumptions about the walleye stock. Catchability, fecundity, and natural mortality schedules could be altered to reflect different biological properties of the population or different fishing regulations. In our analyses, we explored the implications of only two catchability schedules (Schedule 1: $q_1 = q_2 = 0$ and $q_3 = q_4 = 1$; and Schedule 2: $q_1 = 0.17$, $q_2 = 0.43$, $q_3 = 0.82$, and $q_4 = 1.0$) and one fecundity schedule ($k_1 = k_2 = 0$ and $k_3 = k_4 = 1.0$). We also assumed a constant age-specific natural mortality coefficient of 0.2 per year. We obtained strategies to maximize harvest for both catchability schedules, and we explored strategies to minimize variance about various desired harvest levels for catchability schedule 1. These two catchability schedules allowed us to learn the potential difference in optimal strategies that would follow from either exclusively fishing adults (Schedule 1) or including significant juvenile catch (Schedule 2). The fecundity schedule essentially defined which age groups contributed to the adult stock. In this case, we assumed that fish 3 years old and older in the spring were fully reproductive. We did not believe that these were the only schedules worth considering. Rather, we viewed them as convenient starting points.

To have reasonable lengths of computer runs, we had to make several trade-offs between length of computer run and parameter range. For example, the number of states for each age group was six. Because the number of computations increased exponentially by a factor of 4, six states per age group was a practical limit. Unfortunately, this restriction imposes a rather coarse numerical density grid on the analysis. We finally settled on a constant density grid size ($d_j = 2$ million). The effective maximum density of a cohort was thus 10 million at age 1. This limit accounts for over 95% of the historical cohorts in Lake Erie. However, all cohort states under 2 million required interpolation to zero density. A lower grid size is required for more detailed exploitation strategies for age group densities under 2 million fish, but we felt that major trends could be identified at this level of resolution. Finally, to obtain better convergence of control law, we had to discount future values at a rate of about

20% per year.

Results of Analysis

SDP Exploitation Strategies

The optimal exploitation strategies, which we obtained to maximize harvest, showed a strong dependence upon the catchability schedule imposed by gear and fishing regulations. Catchability schedule 2, for example, predicts a lower effort for the same juvenile state (Fig. 3) than does schedule 1 (Fig. 4). Because schedule 2 allows harvest of juveniles, however, the optimal harvest quotas (Fig. 5) for low density states are lower than for schedule 1 (Fig. 6). From Table 1, the median adult density was 2.1 million and the median juvenile density was 5.5 million. Historically, therefore, some 50% of the time the stock was in a state that should have a low level of exploitation. That high levels of exploitation occurred instead tends to support the idea that overfishing led to walleye decline in Western Lake Erie. The strategies in Figs. 5 and 6, however, do suggest that the population should be able to provide large harvests in some ranges of adult and juvenile densities.

If the goal of management were to lower annual variability in catch, optimal exploitation strategies change. The changes in strategy, however, mainly affect harvest at higher adult densities. Figs. 7 to 10 show this pattern of decreasing frequency of high effort as the desired catch decreases from 10 million to 1 million. The optimal strategies were based on catchability schedule 1. At lower adult densities, the optimal expected harvests are not affected as much as at higher adult densities. Fig. 11, for example, is the optimal expected harvest for different adult and juvenile densities to minimize variance of harvest about a desired harvest of three million fish per year.

Simulations Based on SDP Strategies

The different optimal exploitation strategies that we obtained from the SDP analyses produced varied behavior in simulated walleye populations (Table 7). Using the model in equations 7 to 11 with the Ricker stock-recruitment relationship, we found that a strategy maximizing harvest for catchability schedule 2 produced the highest mean annual catch for a simulation period of 100 years. This maximum harvest strategy was implemented by setting the desired harvest at an unattainable level as discussed by Walters (1975). This strategy, however, also had the highest variability of catch and lowest mean adult density. These simulations also demonstrated the effectiveness of strategies designed to reduce variability in the harvest.

Minimizing variance about a desired harvest of 3 million per year, for example, halved the standard deviation of harvest from that obtained for maximizing harvest with catchability schedule 1. Furthermore, the reduced variability resulted in only a 15% drop in mean annual yield and a 30% increase in mean adult density.

Simulations Based on Constant Effort Strategies

Assuming constant effort for 100-year periods, we estimated harvest that could be obtained from simulated walleye populations. The simulations were the same as those for the SDP strategies, but with effort fixed at a constant level. We derived maximum sustainable yield (MSY) curves for both catchability schedules from this model (Fig. 12). Maximum harvest occurred at an annual instantaneous effort of 1.0 per year for catchability schedule 2 and at 2.4 per year for catchability schedule 1. In comparison to the SDP strategies that maximized harvest for these catchability schedules, the MSY models at their optimal efforts had both lower mean annual harvest and lower mean annual adult densities for the 100-year simulation period (Table 8). Although the MSY harvest for catchability schedule 2 seemed to have lower variability than its SDP counterpart, the variance of harvest for the SDP model is probably too high. Because of the coarseness of the density grid for the different age groups, as much as 10% of the simulation period had no harvest. Both mean annual harvest and variance should improve if finer grid size could be used. Nevertheless, these results suggest that annual quota setting can improve fishery performance with adequate information on the state of the stock.

DISCUSSION

Our earlier work indicated that the walleye population in Western Lake Erie could have a more effective management scheme than that practiced in the past (Shuter and Koonce 1977). We felt that an annual evaluation of the stock coupled with known sources of variability in recruitment could be used to recommend catch quota for the following year. Furthermore, we felt that such strategies could yield greater harvests than strategies not dependent on knowledge of the state of the stock. Finally, we felt that the issues arising from this management problem could illuminate some areas of future research. Our findings support these expectations.

Allowing the stock to recover from overexploitation has been a main concern in the management of walleye in Western Lake Erie since 1969. From Table 1, this objective seems to have been realized. The next issue was then maintenance of the stock and prevention of future overexploitation. The procedure used by the

GLFC to extablish quotas for harvest of walleyes is a conservative one (Standing Technical Committee, 1978). Essentially, a low instantaneous fishing mortality (0.1 to 0.2 per year) for a defined fishable stock has formed the basis of quota recommendation. This recommended level of exploitation is in part based on deterministic, equilibrium yield models. Our earlier findings from individual cohort analysis also indicated optimal exploitation at about the same level (Shuter et al. 1979). However, a fishing mortality of 0.2 per year is clearly suboptimal in comparison with the MSY models (Fig. 12) or the SDP analyses (Table 7). Although many additional factors must be considered in recommending a quota, the quotas we derived from the SDP analyses for the period 1976 to 1979 are considerably greater than those actually used (Table 9).

The discrepancy in optimal strategies derived from our earlier cohort studies and those reported here reflects the increased management potential in our current work. Year-class strength variability is a characteristic feature of exploited fish populations with overlapping generations. The resulting variability in age structure violates important assumptions in most deterministic models. In our cohort studies, we focused on optimal strategies to exploit individual cohorts. The major deficiency in this approach was that individual cohort management was not possible. Our current studies are closer to reality in that the models explicitly incorporate known sources of variability in year-class strength and the age structure of the population. If cohort management were used, catches would be more conservative because the weak year classes would be emphasized. The population approach we have developed, however, places a weak year class in some context. If the stock has a strong year class with a weak one, the quotas could be greater, but a series of weak year classes would result in a very low quota recommentation. This difference in quota setting strategies illustrates the importance of greater availability of information to establishing optimal harvests from a fishery.

Another management value of our SDP strategies is their effect on the exploited population. An important difference between the MSY and the SDP strategies in Table 8 is the information required to implement the strategy. The MSY strategies prescribed a constant effort and no annual reevaluation is required. Although both depend upon a stock-recruitment relationship that is derived from historical data, the SDP strategies require in addition annual information on the state of the population. The additional information improves harvest by about 5%. The mean adult density for 100-year simulations, however, is increased by more than 20% and the variance is also reduced (Table 7). The improvement in simulated population behavior is even more striking when SDP strategies are developed to minimize variability in the harvest. Because the adult density is an important component of the variability in year-class strength (Table 6), the tendency of the SDP strategy to stabilize the adult population should also decrease variability in recruitment. The cumulative effect of the greater population stability allowed by using the SDP strategies, therefore, is to make the population less susceptible to uncontrollable and unanticipated stress. As Beddington and May (1977) observed, greater variability in natural populations subjected to exploitation can lead to increased vulnerability to random environmental variability. Furthermore, the management of walleye in Western Lake Erie will influence other species. Less variability in the walleye population may also help dampen variability in species like yellow perch.

The increased management potential of the SDP strategies thus seems substantial. Simulations suggested that these strategies could yield a mean annual harvest of about 3 million walleye per year from Western Lake Erie. This catch level seem sustainable from either of two extreme catchability schedules, and it could, with appropriate regulation, result in improved population stability. The additional research effort required to provide annual evaluations of the state of the stock thus seem to be well worth their cost. In addition, these SDP analyses have raised several research/management questions, and their resolution will contribute even more to the management potential of this and other Great Lakes fisheries.

A central assumption in the development of the SDP strategies was that a stock-recruitment relationship existed for this population. We have tried to document this relationship well because of its pivotal importance. However, we are not totally confident in the Ricker type of relationship that we have employed. For biological reasons, we prefer it to the relationship used in our earlier analyses, but our preliminary comparisons suggested that quota recommendations could be very sensitive to the stock-recruitment relationship. The sensitivity is due to a density-dependent decline in recruitment at densities greater than 5 million adults (Fig. 12). The 1977 year class, however, represents a unique opportunity for experimental management. This year class should begin to contribute to the adult stock in 1980. Based on the Ricker stock-recruitment relationship, therefore, we expect the 1980 year class to be depressed--perhaps being one of the weakest year classes ever observed. Continuation of YOY assessments will be important to test and perhaps modify the stock-recruitment relationship.

This extraordinary year class also provides an opportunity to identify additional components of variability in year-class strength of walleye. Adult stock and rate of spring warming only account for about half of the total variability. We have attempted to extend the analysis, but without much success. We found a possible relationship to yellow perch density. Because the 1977 year class is so large, the population regulation may begin to resemble that observed in smaller water bodies (Forney 1976). Cannibalism may, therefore, be the mechanisms that leads to year class failure predicted by the Ricker stock-recruitment relationship. Additionally, analysis of the relationship between perch and walleye year-class strength may improve the stock-recruitment relationship for walleye in Western Lake Erie.

The increased population density of walleye, however, may also have some adverse consequences for other species in Lake Erie. Although not as well documented, yellow perch seem to be influenced by climatic variability in the same way as walleye (Koonce et al. 1977). Prior to 1969, walleye and perch year-class strength showed some synchrony (Nepszy 1977; Koonce et al. 1977), but yellow perch have not recovered as well as walleye (Nepszy 1977). The reasons are probably complex, but the recent strong year classes of walleye must be affecting young-of-the-year survival for perch. In fact our analyses of Lake Erie data indicate a relationship between walleye recruitment and yellow perch adult density. The link is admittedly tenuous, but we feel it illustrates the necessity of thinking about walleye management in a whole fisheries context, and of initiating research/management efforts to understand these relationships.

In conclusion, we feel that our study has accomplished its objectives. By considering variabililty underlying population regulation in Western Lake Erie walleye, we have found a range of exploitation strategies, which represent different assumptions and management objectives. Explicit consideration of these assumpitons and management objectives is an important area of future work. As others have indicated (Huang et al 1978; Silvert 1978), a management program designed to test the validity of the assumptions or management objectives may have several benefits. In the case of the walleye population in Western Lake Erie, these research/management programs could result in more efficient exploitation of the fishery and a better understanding of the effects of walleye harvest strategies on other species like yellow perch.

Our research would not have been possible without the efforts of many agencies and individuals. These collective efforts, however, have provided a long term data record that is valuable. From an ecological perspective, these data provide a unique possibililty to study the long-term behavior of a natural population subjected to a variety of stresses. From a management point of view, these data provide the foundation for incorporating known sources of variabililty in recruitment in to the development of exploitation stragegies. The richness of this data set is just beginning to become apparent.

RECOMMENDATIONS

Our interpretation of the results of this study indicate three specific lines of inquiry that should be pursued:

1. Application of dynamic modeling techniques should next be applied to the yellow perch data from Lake Erie. Sources of variability in year-class strength seem to be similar to walleye, and we feel that exploitation strategies for walleye must include a consideration of the consequences for yellow perch population dynamics.

2. The SDP strategies we have explored represent a useful starting point, but they are not fully responsive to the needs of the quota setting procedure. The fishable stock defined by fishery regulation does not correspond exactly to any of the catchability schedules we assumed. Furthermore, the fecundity schedule we assumed may be too liberal. The sensitivity of the strategies and quota recommendations to these assumptions needs more thorough analysis. In addition, our analyses focused on harvest as the primary feature for analysis. Because of density-dependent regulation of growth rates, more efficient strategies might be developed by using adult density or fishable stock as the determinants of exploitation strategies.

3. Because of the importance of the walleye resource, the implications of our studies should be more carefully explored in an economic and social context. Such a team approach would be useful in approaching some real problems confronting those who make decision about exploitation of different species in Lake Erie. With the data available for Lake Erie fisheries, we think that Lake Erie would be an appropriate subject for such a team study.

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Table 1. Summary of indices of reproductive potential,recruitment, and rate of water temperature increase in spring for Western Lake Erie during the period 1947-1978.

Year	Egg Density (billions)	Adult Density (millions)	Recruit Density at t+2 (millions)	Temperature Slope (deg C/day)
1947	118.4	9.300	5.670	0.18
1948	137.7	6.900	5.200	0.19
1949	68.9	5.560	6.100	0.21
1950	84.0	7.450	2.980	0.22
1951	72.2	7.100	2.980	0.23
1952	73.3	7.370	7.100	0.27
1953	72.0	4.790	1.200	0.18
1954	59.5	3.520	5.420	0.21
1955	87.9	5.390	2.910	0.29
1956	53.7	1.750	1.290	0.20
1957	88.6	3.320	0.434	0.21
1958	93.3	2.640	0.206	0.17
1959	34.4	0.744	3.330	0.24
1960	16.9	0.310	0.114	0.18
1961	4.8	0.103	0.414	0.24
1962	27.9	0.697	3.590	0.29
1963	11.7	0.196	0.558	0.20
1964	1.8	0.036	0.527	0.32
1965	12.8	0.320	1.970	0.36
1966	5.1	0.101	0.165	0.10
1967	5.9	0.136	0.243	0.13
1968	36.8	0.941	0.318	0.12
1969	12.1	0.237	0.973	0.24
1970	8.6	0.198	5.280	0.31
1971	2.1	0.051	0.580	0.21
1972	19.5	0.490	4.020	0.20
1973	108.0	2.650	1.270	0.17
1974	98.1	1.760	9.500	0.19
1975	134.9	2.630	5.050	0.00
1976	117.1	1.910	1.310	0.14
1977	301.0	6.240	22.100	0.27
1978	436.0	8.230	0.819	0.24

Table 2. Coefficients of determination for correlations between observed and predicted recruitment index (n=21). Coefficients are reported for both untransformed and log transformed indices. Type of stock index and the text equation number of the stock-recruitment relationship are also summarized.

Index of Reproductive Potential	Text Equation	R SQ Untransformed Data	R SQ Transformed Data
Eggs	1	0.329	0.546
Eggs	2	0.334	0.569
Adults	1	0.342	0.555
Adults	2	0.444	0.648
None	3	0.007	0.168
None	4	0.019	0.230

Table 3. Coefficients of determination for correlations between observed and predicted recruitment indices for the period 1968-78. Parameters for Eqs. 1 to 4 (in text) were obtained by fitting the equations to 1947-67 data. Coefficients are reported for untransformed and log transformed recruitment indices. Type of stock index and text equation number of the stock-recruitment relationship are also summarized

Index of Reproductive Potential	Text Equation	R SQ Untransformed Data	R SQ Transformed Data
Eggs	1	0.642	0.450
Eggs	2	0.351	0.279
Adults	1	0.564	0.301
Adults	2	0.412	0.312
None	3	0.187	0.284
None	4	0.170	0.274

Table 4. Coefficients of determination of different stock-recruitment relationships (Eq. 1 and 2 in text) for time series 1947-64 (n=18) and 1964-78 (n=14). The index of reproductive potential is indicated.

Index of Reproductive Potential	Text Equation	R SQ for 1947-64	R SQ for 1964-78
Eggs	1	0.453	0.713
Adults	1	0.533	0.685
Eggs	2	0.507	0.522
Adults	2	0.586	0.521

Table 5. Summary of mean monthly precipitation, mean monthly significant wave height, and annual yellow perch harvest data used in stepwise multiple correlations with walleye recruitment.

	Mean Preciptation		Mean Wave Height		Yellow Perch Harvest
Year	April (cm/day)	May (cm/day)	April (m)	May (m)	(1000 MTons)
1947	10.770	12.116	1.158	1.158	1.750
1949	6.401	10.871	2.499	2.073	2.140
1950	15.164	4.166	2.530	1.219	2.100
1951	7.645	6.883	1.158	1.494	2.340
1952	7.366	9.195	1.097	1.463	1.720
1953	6.198	8.077	1.494	1.006	3.360
1954	7.772	4.216	1.311	1.859	5.630
1955	5.639	3.505	0.945	1.158	3.210
1956	4.953	12.014	2.073	0.914	8.420
1957	10.770	5.563	3.658	2.073	9.280
1958	5.080	5.817	1.311	0.823	10.150
1959	9.322	10.033	2.438	1.798	13.120
1960	4.115	7.899	1.859	0.975	8.160
1961	12.548	5.461	1.372	1.524	9.560
1962	4.572	7.188	3.109	3.719	12.820
1963	5.512	6.680	1.981	0.884	10.740
1964	8.865	2.438	0.884	0.945	4.520
1965	5.258	9.652	1.524	0.884	9.800
1966	7.137	4.775	1.829	1.676	11.220
1967	7.036	5.791	1.890	0.732	11.570
1968	7.645	11.963	1.158	1.890	12.790
1969	9.246	9.500	1.585	1.737	15.100

Table 6. Summary of the results of a stepwise multiple correlation of various factors associated with recruitment (n=22). Factors entered at each step were 1) Log adult density, 2) Temperature slope, 3) Mean May wave height, 4) Mean May precipitation, 5) Annual yellow perch harvest, 6) Mean April precipitation, and 7) Mean April wave height.

Step	Multiple R SQ	Increase in R SQ	F Value to Remove
1	0.403	0.403	13.5
2	0.660	0.257	14.4
3	0.697	0.037	2.2
4	0.720	0.023	1.4
5	0.762	0.042	2.8
6	0.772	0.010	0.6
7	0.779	0.007	0.4

Table 7. Summary of harvest and adult density statistics from 100-year simulations of optimal strategies to minimize variance about various desired harvest levels. The catchability schedule used is also specified.

Catchability Schedule	Desired Harvest (millions/yr)	Mean Annual Harvest (millions)	S. D. Annual Harvest (millions)	Mean Adult Density (millions)	S. D. Adult Density (millions)
1	100	3.40	2.55	4.66	2.58
2	100	3.94	2.83	3.98	1.27
1	50	3.40	2.55	4.66	2.58
1	10	3.33	1.98	4.91	2.54
1	5	3.21	1.55	5.16	2.64
1	3	2.98	1.27	5.50	2.71
1	1	1.75	0.85	7.50	2.75

Table 8. Comparison of harvest and population density statistics for 100-year simulations of walleye populations. Optimal strategies were either from maximum sustainable yield (MSY) model or a stochastic dynamic programming (SDP) model. Catchability schedule is also indicated.

Model and Version	Catchability Schedule	Mean Annual Harvest (millions)	S.D. of Annual Harvest (millions)	Mean Adult Density (millions)	S.D. of Adult Density (millions)
MSY	1	3.24	2.43	3.79	2.84
MSY	2	3.76	1.51	3.24	1.82
SDP	1	3.40	2.55	4.66	2.58
SDP	2	3.94	2.83	3.98	1.27

Table 9. Comparison of harvest quotas recommended for walleye harvest in Western Lake Erie by the GLFC with quotas derived from two different SDP strategies, which differ in catchability schedules. Catchability schedule 1 allows only adult harvest and catchability schedule 2 allows some juvenile as well as adult harvest.

	Quota	(millions)	
		SDP Catchability Schedule	
Year	Recommended	1	2
1976	0.945	1.7	1.7
1977	0.995	5.6	5.9
1978	0.827	5.4	11.2
1979	2.560	6.7	16.5

FIGURE LEGENDS

Fig. 1. Stock-recruitment relationships used in models. A. Shows two relationships using adult density as an indicator of reproductive potential (solid line is eq. 2 and the dotted line is eq. 1). B. Shows a Ricker type curve based on egg density as a measure of reproductive potential. All curves assume a$\Delta T/t$ of 0.225 deg C/day.

Fig. 2. Comparison of the observed 2-yr old recruits with those predicted by the Ricker stock-recruitment relationship for the period 1947-78. Data are taken from Table 1.

Fig. 3. Frequency distribution of effort for various juvenile states (I1 + I2) for catchability schedule 2. This graph represents the absolute number of population states out of 1296 associated with a particular juvenile state and effort level. The desired harves was 100 million fish.

Fig. 4. Frequency distribution of effort for various juvenile states (I1 + I2) for catchability schedule 1. This graph represents the absolute number of population states out of 1296 associated with a particular juvenile state and effort level. The desired harves was 100 million fish.

Fig. 5. Harvest quota expected for different juvenile and adult densities. Parameter conditions were catchability schedule 2 and a desired harvest of 100 million fish.

Fig. 6. Harvest quota expected for different juvenile and adult densities. Parameter conditions were catchability schedule 1 and a desired harvest of 100 million fish.

Fig. 7. Frequency distribution of effort for various juvenile states (I1 + I2) for catchability schedule 1. This graph represents the absolute number of population states out of 1296 associated with a particular juvenile state and effort level. The desired harves was 10 million fish.

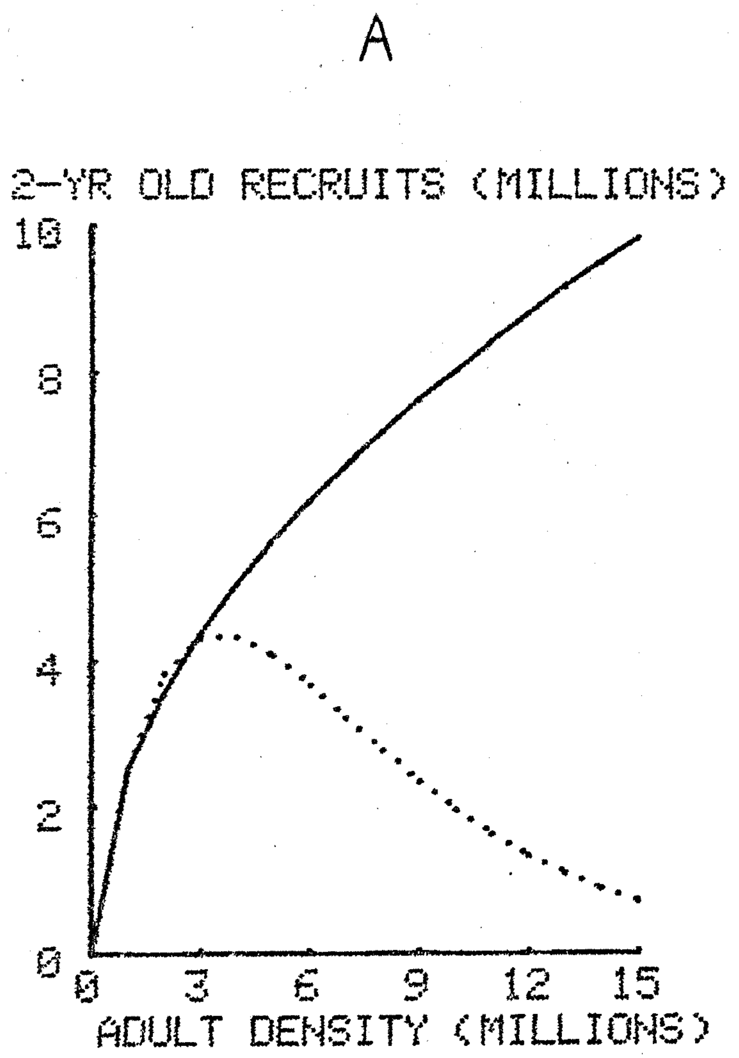
Fig. 8. Frequency distribution of effort for various juvenile states (I1 + I2) for catchability schedule 1. This graph represents the absolute number of population states out of 1296 associated with a particular juvenile state and effort level. The desired harves was 5 million fish.

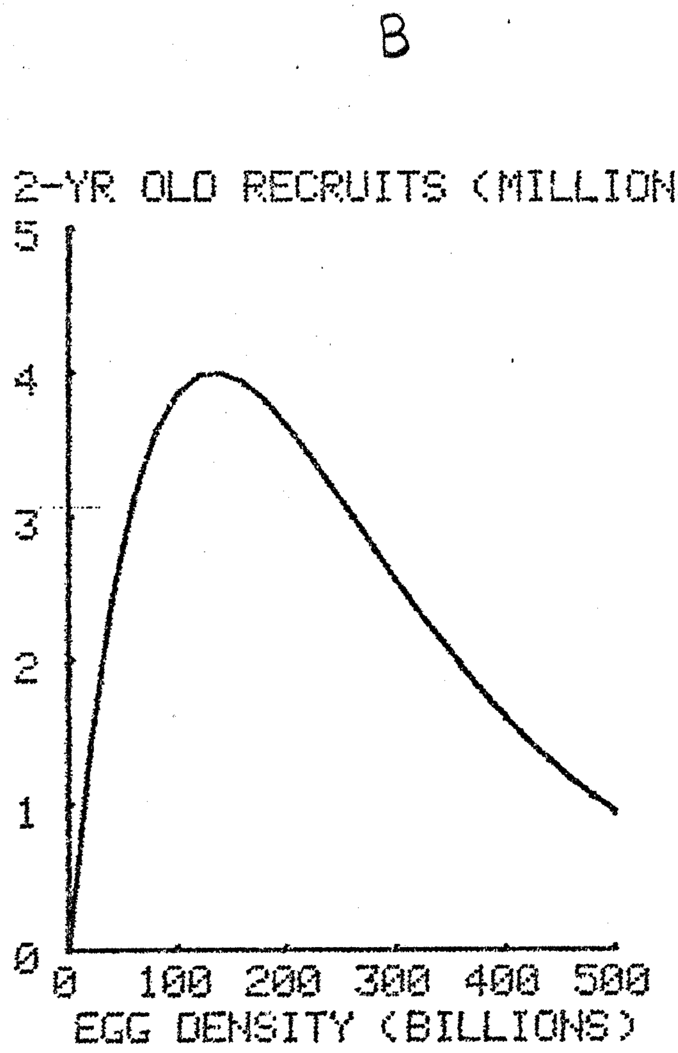
Fig. 9. Frequency distribution of effort for various juvenile states (I1 + I2) for catchability schedule 1. This graph represents the absolute number of population states out of 1296 associated with a particular juvenile state and effort level. The desired harves was 3 million fish.

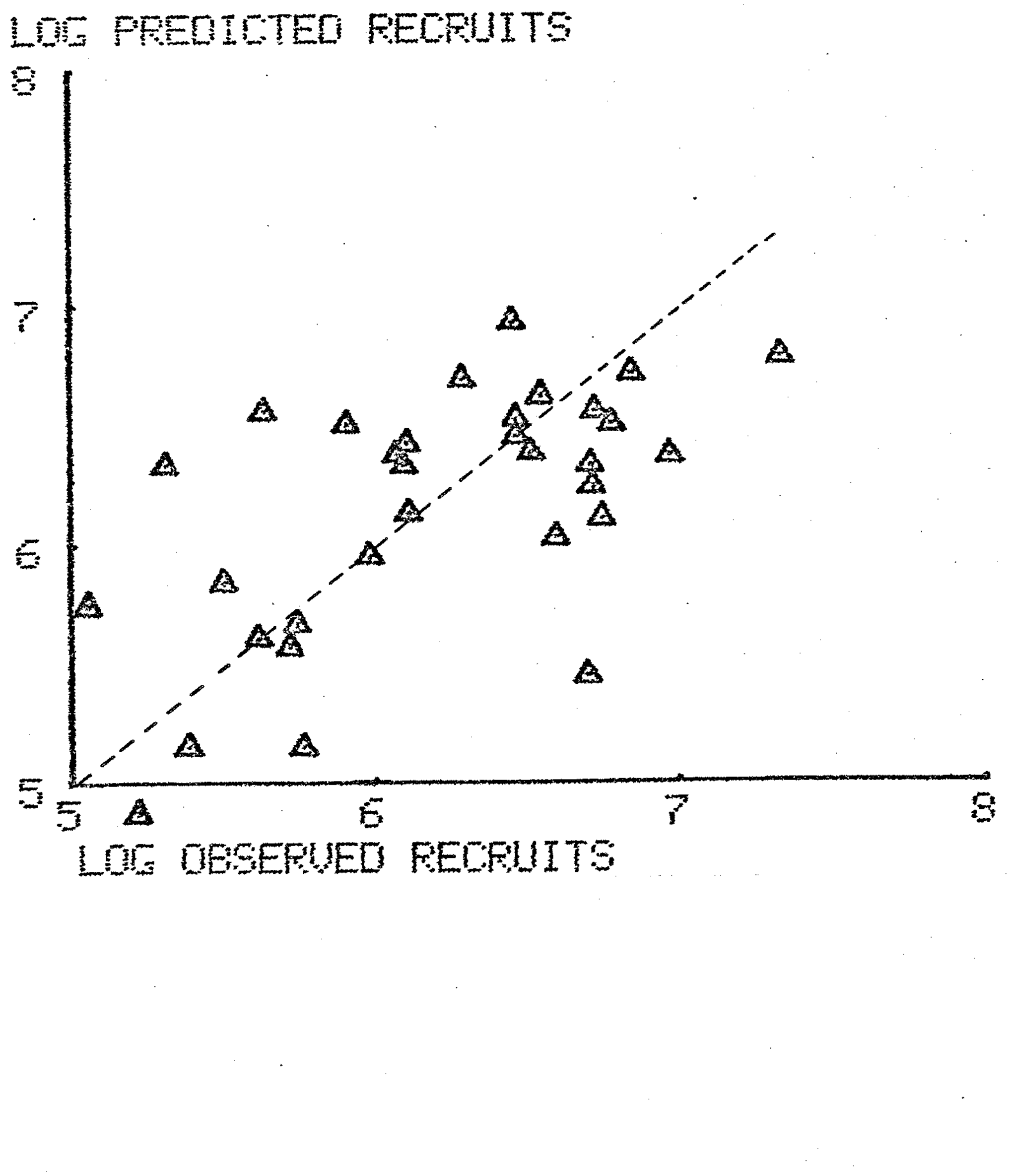
Fig. 10. Frequency distribution of effort for various juvenile states (I1 + I2) for catchability schedule 1. This graph represents the absolute number of population states out of 1296 associated with a particular juvenile state and effort level. The desired harves was 1 million fish.

Fig. 11. Harvest quota expected for different juvenile and adult densities. Parameter conditions were catchability schedule 1 and a desired harvest of 3 million fish.

Fig. 12. Mean annual harvest from populations subjected to various constant efforts for 100-year periods. All simulations assumed a natural mortality of 0.2 per year for all ages of fish. (X------X) is the result for catchability schedule 2, and (□——□) is the result for catchability schedule 1.


A
2-YR OLD RECRUITS (MILLIONS)
10
8
6
4
2
0
0
3
6
9
12
15
ADULT DENSITY (MILLIONS)


B
2-YR OLD RECRUITS (MILLIONS)
5
4
3
2
1
0
0
100
200
300
400
500
EGG DENSITY (BILLIONS)


LOG PREDICTED RECRUITS
8
7
6
5
5
6
7
8
LOG OBSERVED RECRUITS

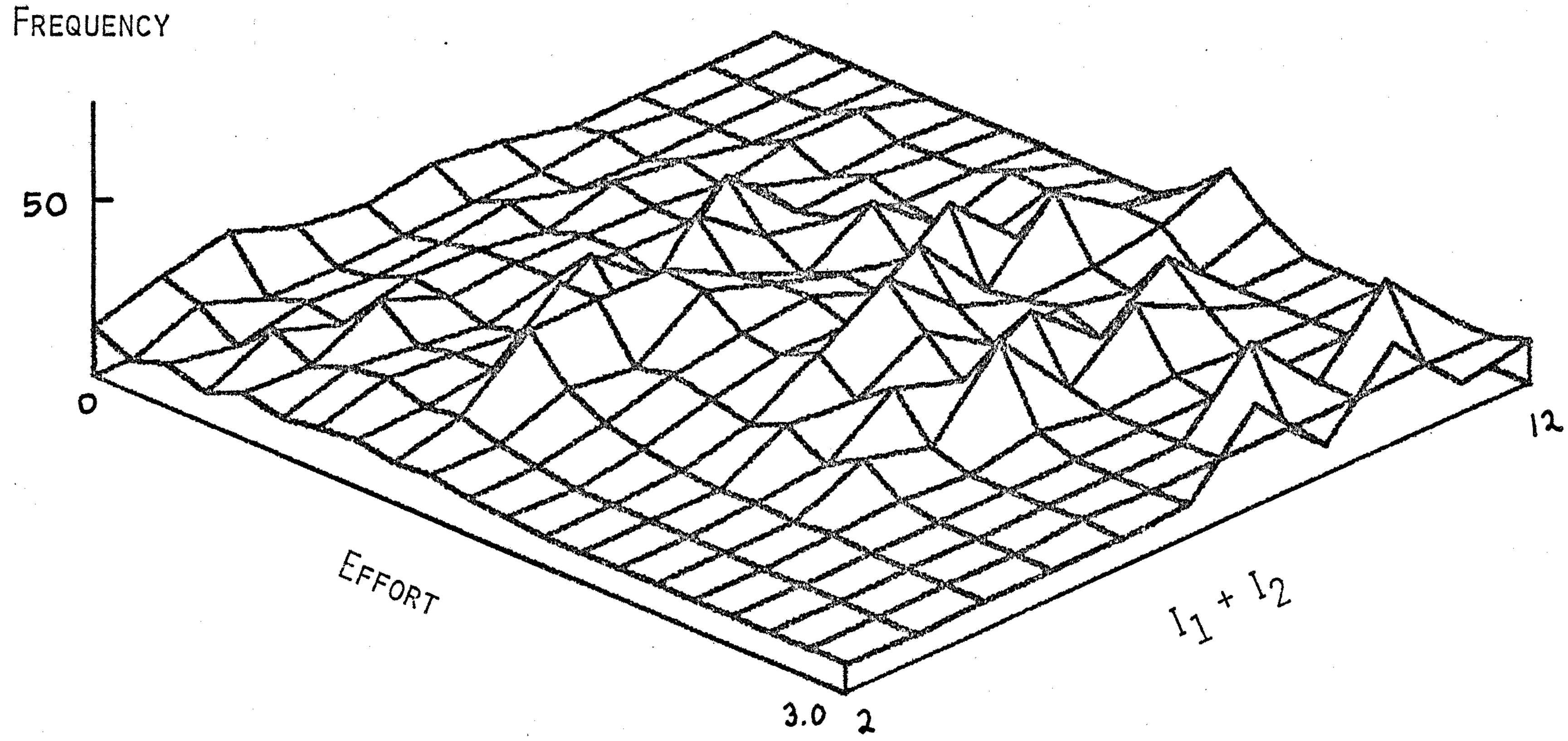
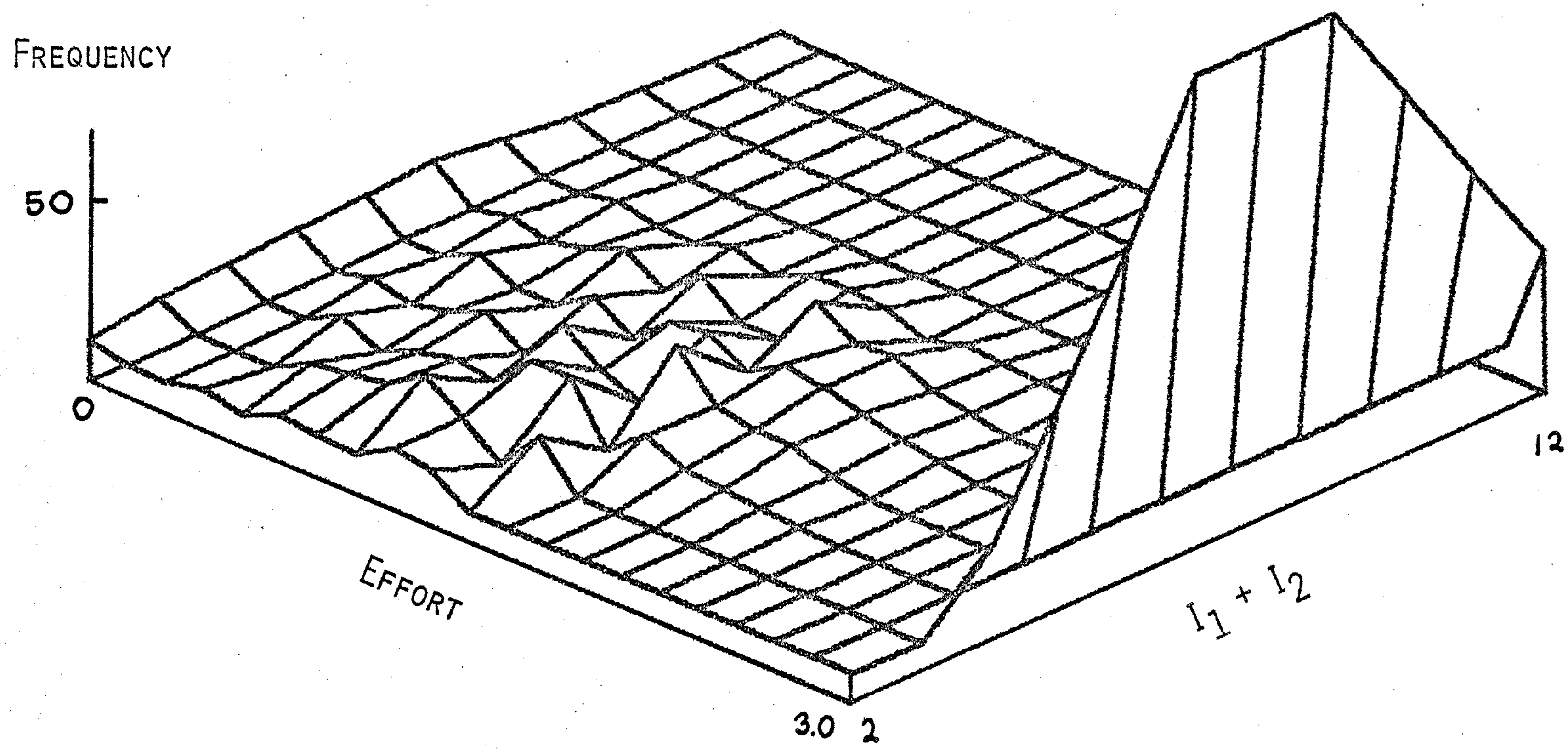

FREQUENCY
50
0
EFFORT
3.0
2
$I_1 + I_2$
12

Fig. 4



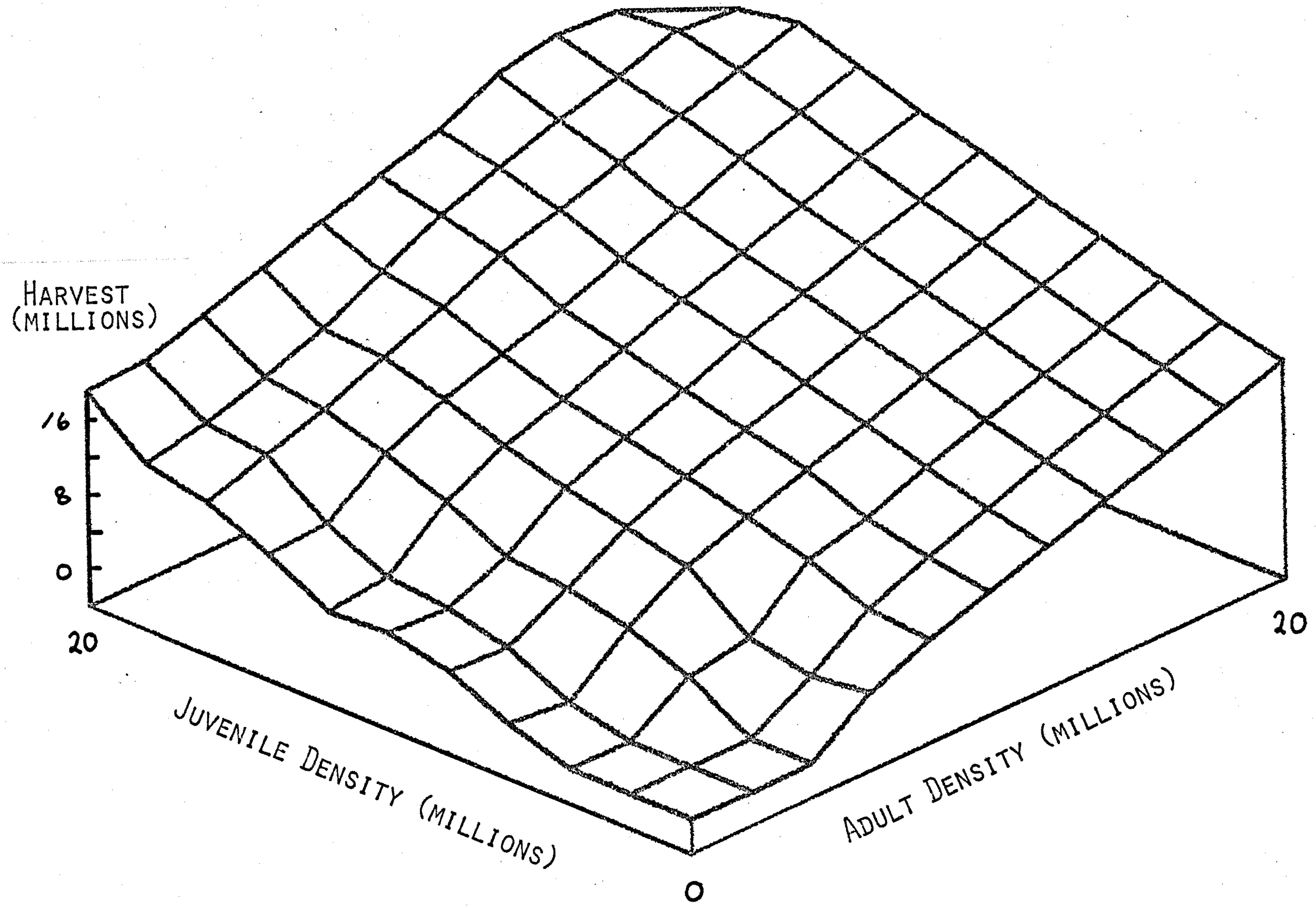

HARVEST (MILLIONS)
16
8
0
20
JUVENILE DENSITY (MILLIONS)
0
ADULT DENSITY (MILLIONS)
20

Fig. 6

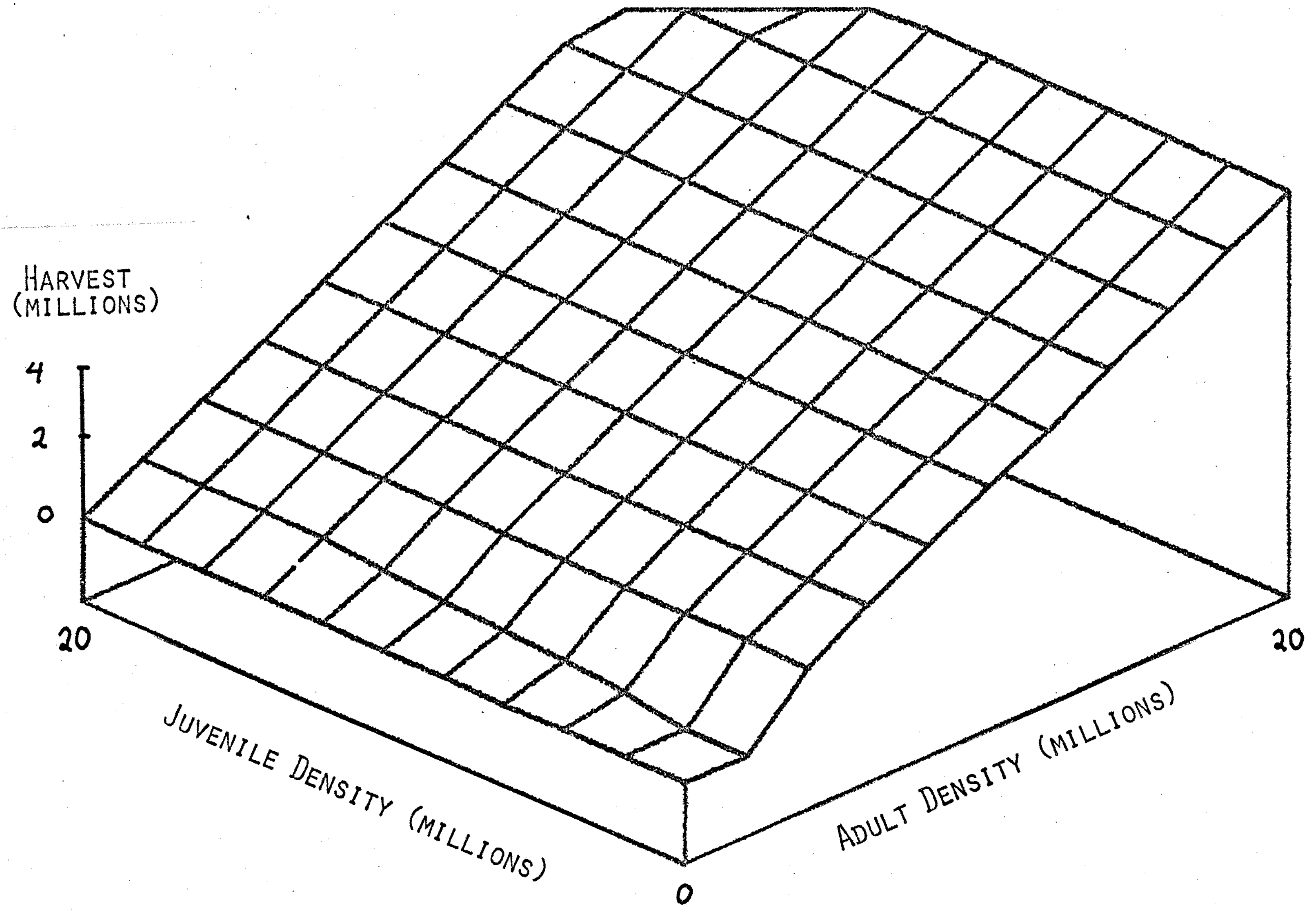
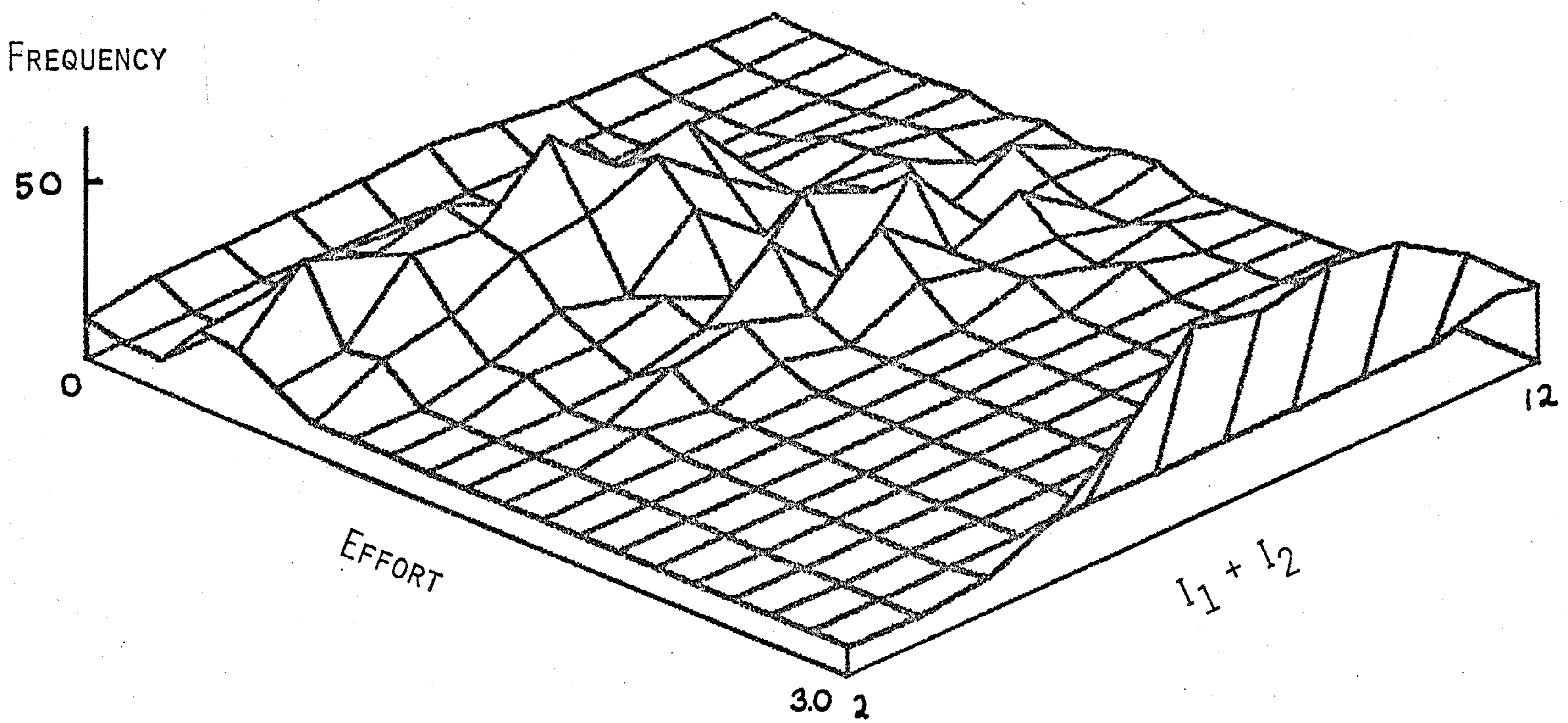

HARVEST
(MILLIONS)
4
2
0
20
JUVENILE DENSITY (MILLIONS)
0
ADULT DENSITY (MILLIONS)
20

Fig. 1



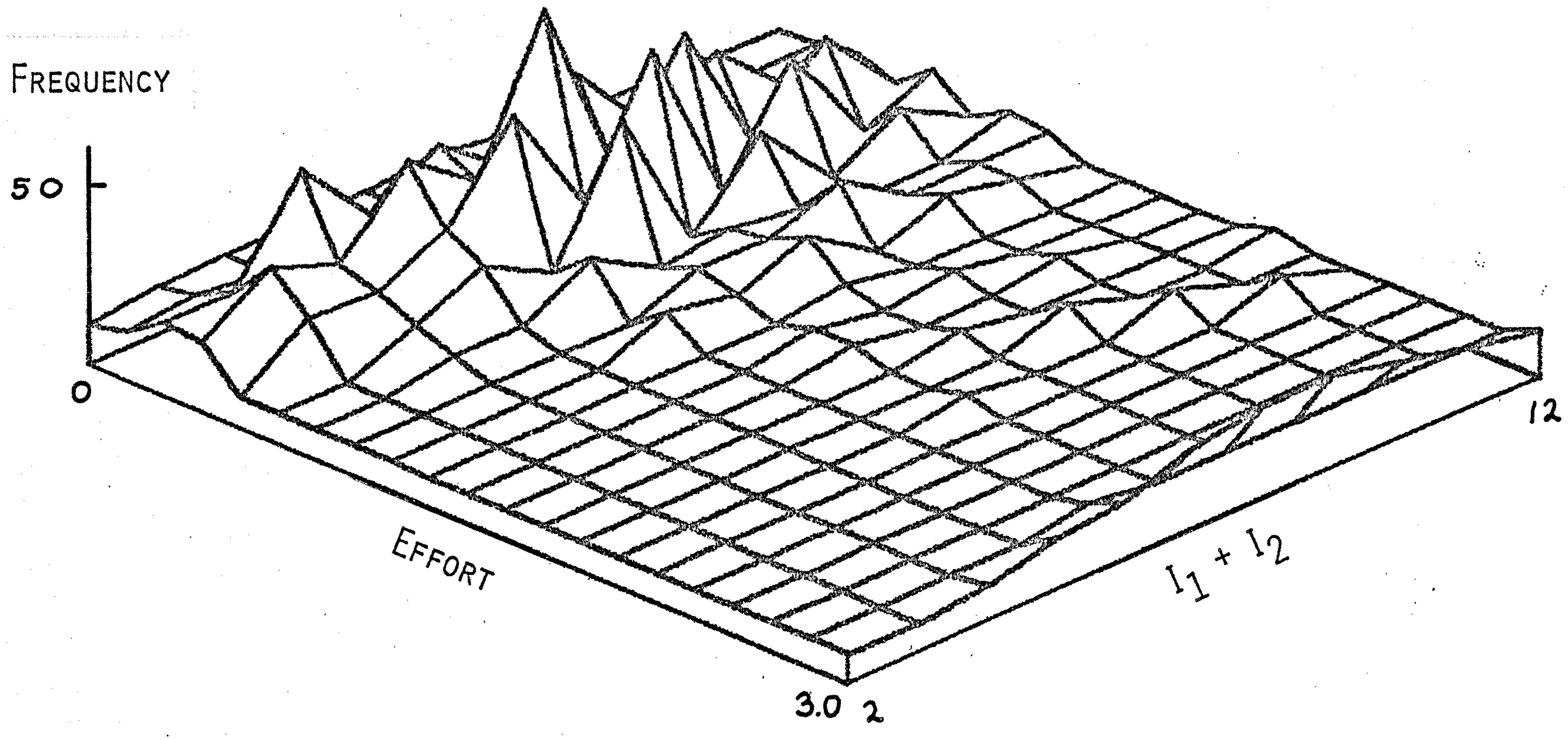

FREQUENCY
50
0
EFFORT
3.0
2
$I_1 + I_2$
12

Fig. 7

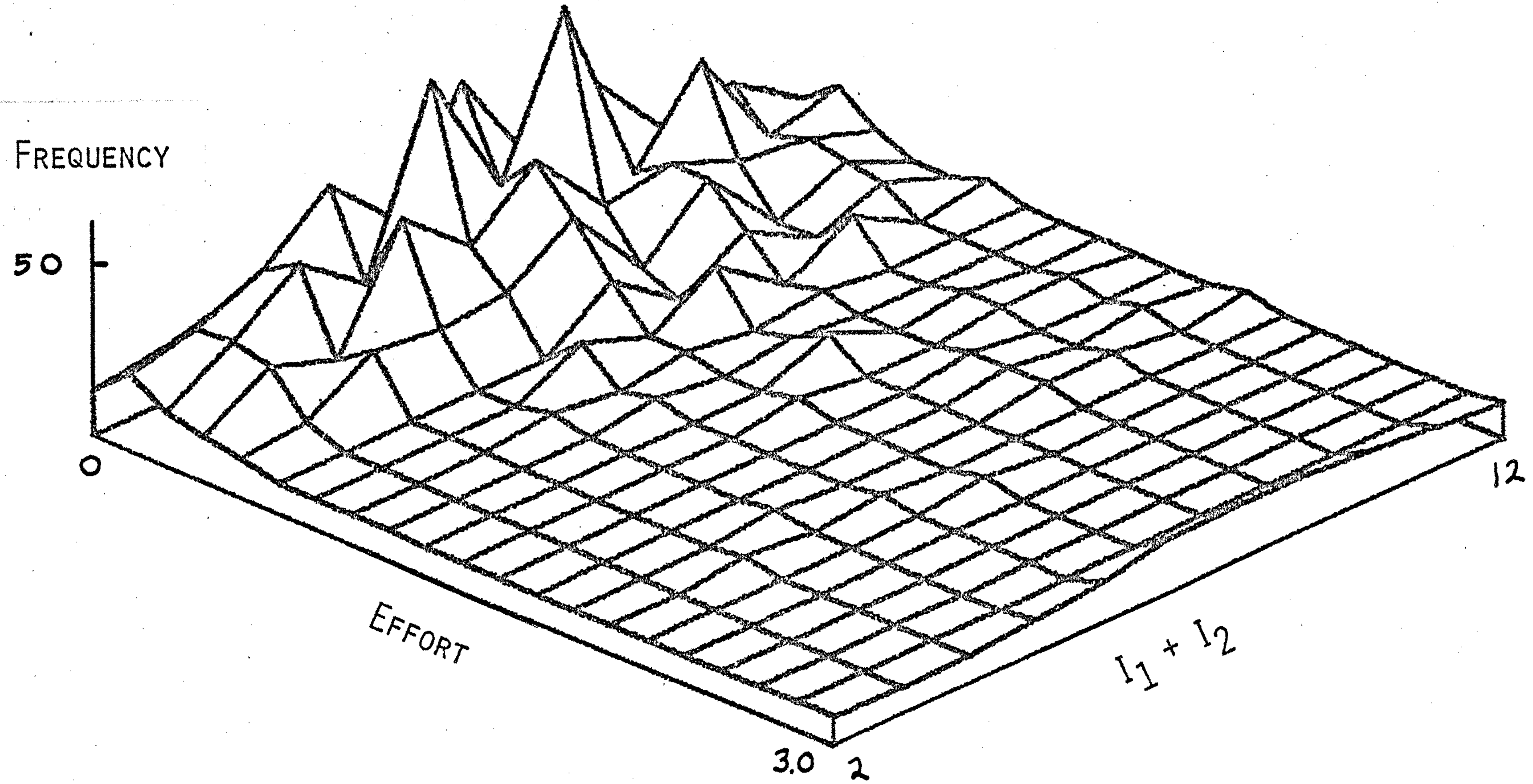


Fig. 10

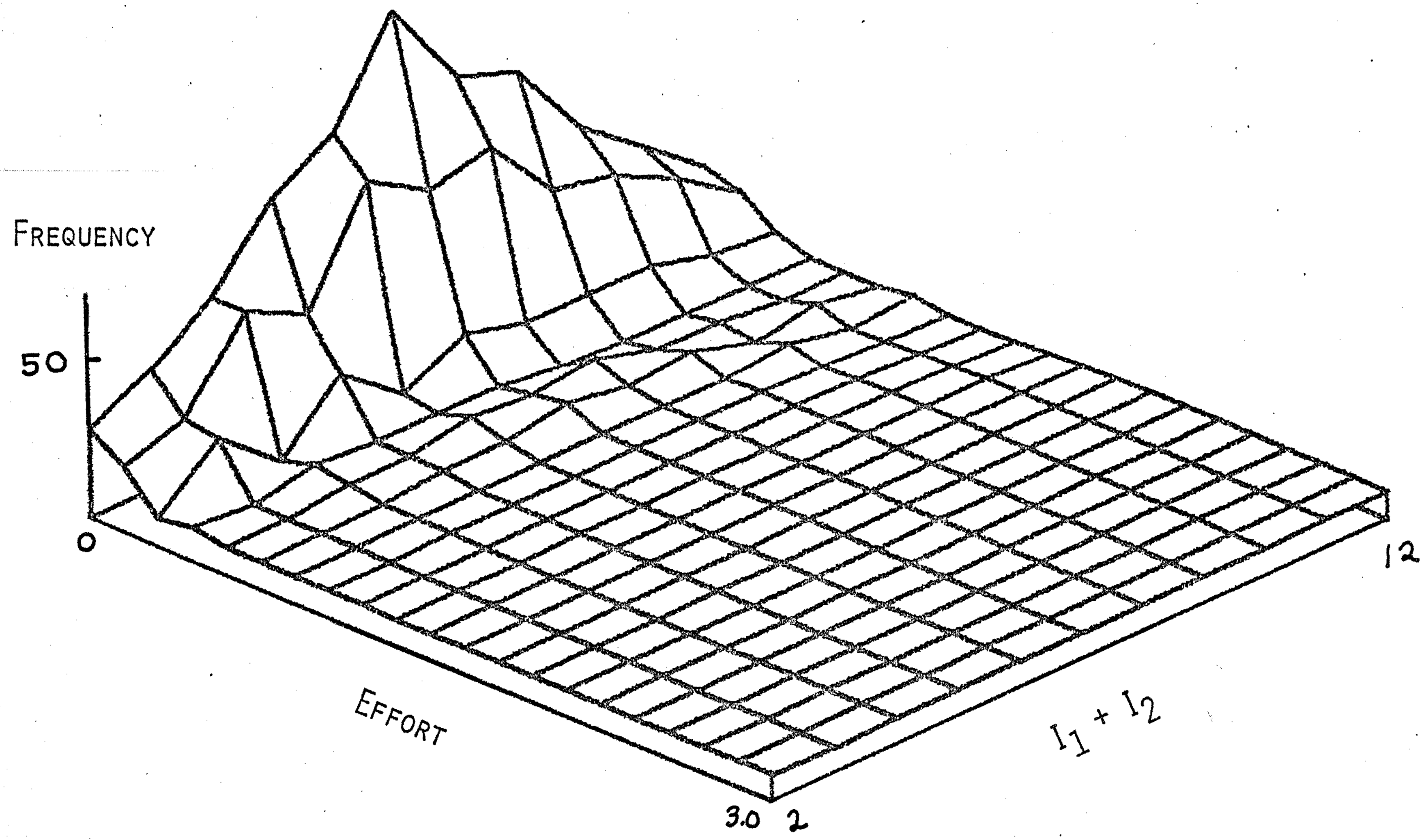


Fig. 11

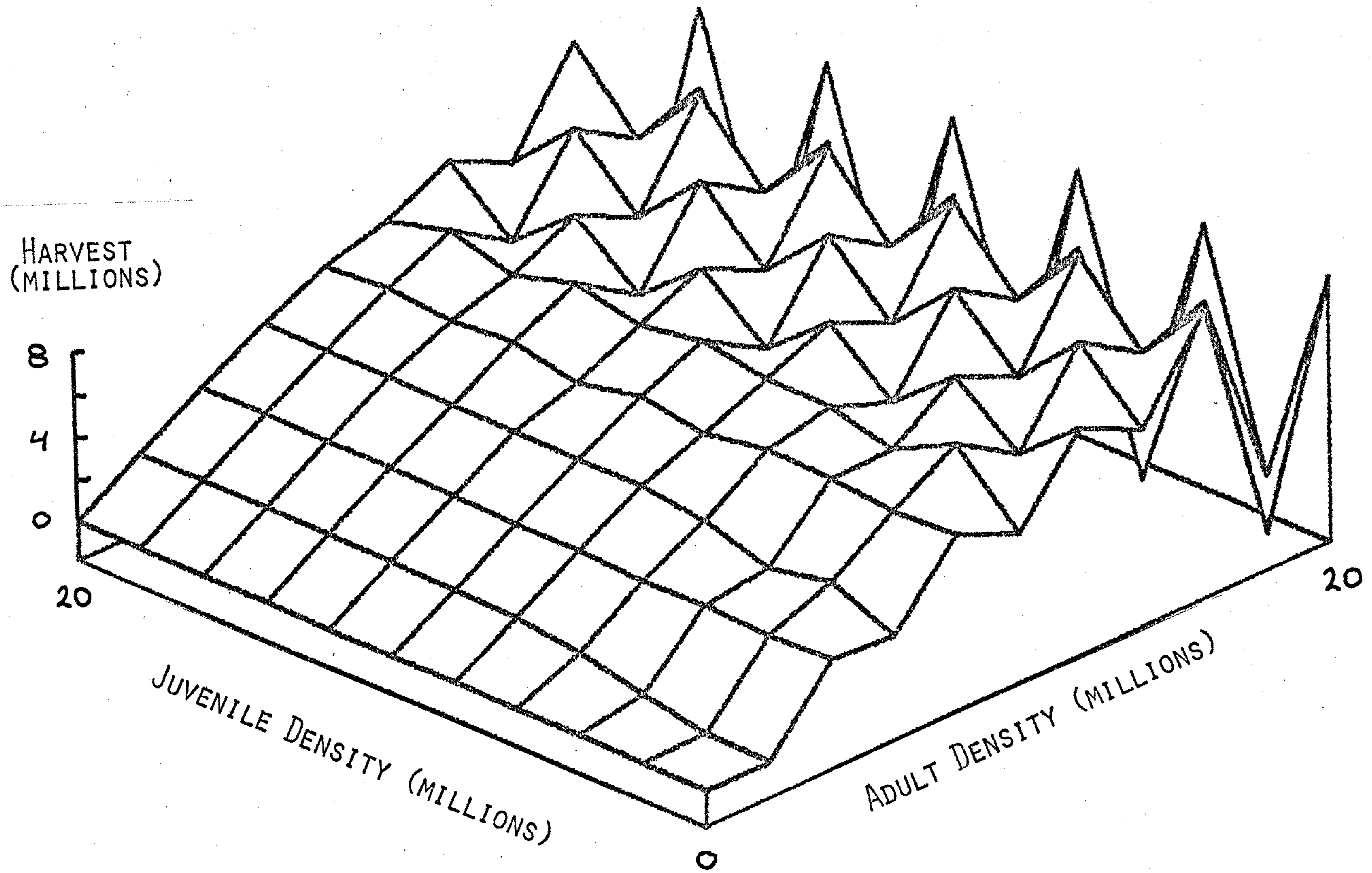
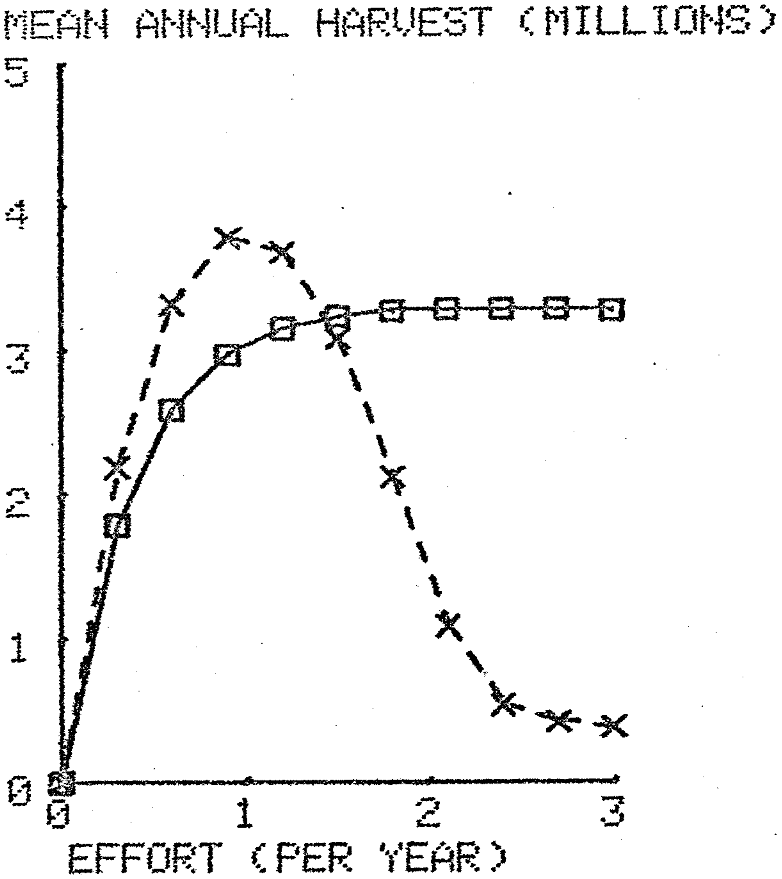

HARVEST (MILLIONS)
8
4
0
20
JUVENILE DENSITY (MILLIONS)
0
ADULT DENSITY (MILLIONS)
20

Fig. 12



APPENDIX A

Documentation of Stochastic Dynamic Programming Model

Program and Documentation

by

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Baton Rouge, Louisana

OVERVIEW

This is a brief description of the program developed on the CWRU, Biology Dept., PDP 11/34 computer for the calculation of optimal fishing efforts in a stochastic environment. The program, as presently coded, considers four age classes, yearlings, 2, 3, and 4+ year olds. Recruits are calculated to enter directly into the yearling class of the following year. Recruitment is a random variable depending on rate of spring warming as well as stock size. Fishing and non-fishing mortality are assumed to occur after reproduction. Population sizes therefore refer to the spring populations prior to harvest. The optimal fishing mortality rate is calculated as a function of the population of each age class. Optimal effort is, therefore, a function of four variables. Storing the value of this function for six different population levels of each of the four age classes results in 6*6*6*6 = 1296 values being calculated. Memory and time constraints of the computer system therefore clearly limit the extension of this stochastic dynamic programming technique. Typically about 10 minutes are required for each year (or stage) calculated. Ten or more years are often required for convergence to a stationary harvest strategy. This program demonstrates that stochastic dynamic programing is a feasible and straight forward approach for the determination of optimal fishing strategies based on stock recruitment relationships. Population models with more than four of five state variables will require the application of other optimization techniques.

The computer program is written in FORTRAN. The program is structured using subroutines to calculate recruitment, death, and the objective function. This results in greater tractability of the program logic and enhances the flexibility of program alteration and testing.

MODEL

1. Mortality:

```
W1(I+1)=W(I)*exp(-DEATH(I)-CATCH),   I=1,2,3
W1(4)=W(3)*exp(-DEATH(3)-CATCH)
      +W(4)*exp(-DEATH(4)-CATCH),   I=4
CATCH=SELECT(I)*(FMIN+F1*DF)
```

where W and W1 are the population sizes, DEATH(I) is the non-fishing mortality rate, CATCH is the fishing mortality rate, SELECT(I) is the selectivity of age class I to fishing, FMIN is the minimum fishing mortality, DF is the increment in fishing mortality, and F1 is an integer 0<=F1<NF determining fishing intensity.

2. Recruitment:

```
STOCK=sum FECNDY(I)*W(I)/1.0E6,   I=1,2,3,4
RECRUT=1.0E6*(0.2828*STOCK*EXP(-0.284*STOCK+11.99*DT))
```

where FECNDY(I) is the fraction of W(I) to be included in the stock, DT is the rate of spring warming (Deg C/day), and RECRUT is the size of the following yearling population.

3. Objective:

```
max sum H*DSCNT**(NSTAGE-j),   j=ISTAGE,...,NSTAGE
 F1
```

where H is the total harvest, and DSCNT is the discount rate.

PROGRAM ORGANIZATION

Calling sequence:

```
  Main Program
    MAX
      PROFIT
        DEATHC
        RECRUT
        VALUE
```

MAX - Searches for the maximum value of a function, returns value of function at its maximum and the argument which maximizes the function.

`CALL MAX(FUNC,VALU,CONTRL)`

FUNC is a FUNCTION subroutine with one argument

CONTRL Maximizing integer argument of FUNC.

VALU is the maximum value.

PROFIT - FUNCTION subroutine, returns value of objective function for the present stage plus future stages. Objective function is defined in this routine.

`X=PROFIT(CONTRL)`

CONTRL is fishing intensity, an INTEGER.

DEATHC - Given population at stage n and fishing intensity, calculates population at stage n+1 for ages 2 - NSTATE.

`CALL DEATHC(F1,H)`

F1 is fishing intensity, an integer

H is harvest, an output.

RECRUT - Calculates recruitment and stock given rate of warming, DT.

X=RECRUT(DT)

VALUE - Interpolates value of future objective function at population level W2. Uses NSTATE dimensional matrix, P, of future values of the objective at specific population levels. A FUNCTION subprogram.

X=VALUE(W2)

COMMON VARIABLES

1. PARAMETERS

FECNDY(NSTATE)- Fecundity, used in RECRUT to weight age classes in STOCK calculation.

DEATH(NSTATE)- Death rate (base e) used in DEATHC for non-harvest death.

SELECT(NSTATE)- Catch selectivity used in DEATHC to calculate harvest mortality.

PDT(NDT)- Probability of DT values.

NDT- Number of DT values.

DDT- Increment between DT values.

DTMIN- Minimum DT value calculated.

NSTATE- Number of age classes.

NSTAGE- Maximum number of stages (years) to be calculated.

NGRID- Number of values in each age group.

FMIN- Minimum harvest mortality (base e) considered.

DF- Increment in harvest mortality.

NF- Number of harvest mortality values considered.

DW(NSTATE)- Grid separation for each age class.

DESHAR- Desired harvest level.

2. OUTPUTS

STOCK- Stock size.

W(NSTATE)- Population sizes for this year.

W1(NSTATE)- Population sizes for next year.

P(NGRID,...,NGRID)-NSTATE dimensional array of values of objective function for next year.

PP(NGRID,...,NGRID)- This year's P array.

3. PROGRAM CONTROL

DFSTOP- Stopping criteria for convergence to stationary effort, execution stops if DF2<DFSTOP for at least two stages.

I1,I2,I3,I4- Grid indicies for age classes, subscripts for P.

4. LOGICAL UNIT NUMBERS

ITTI- Terminal input.

ITTO- Terminal output.

ILP- Line printer output.

IDB-Debugging information output.

IF1,IF2,IF3- File I/O.

5. EFFORTS

F(NGRID,...,NGRID)- Present effort indicies NSTATE dimensional integer array.

FF(NGRID,...,NGRID)- Next year's F array.

6. FLAGS

NOQUER- 1 output query to terminal, 2 does not query.

IDFFLG- Flag for stopping criterion.

PROGRAM LISTING

```
C     PARAMETERS
      COMMON FECNDY(4),DEATH(4),SELECT(4)
      COMMON PDT(20),NDT,DDT,DTMIN,NSTATE,NSTAGE,NGRID
      COMMON FMIN,DF,NF
      COMMON DSCNT, DESHAR
C     OUTPUTS
      COMMON DW(4),STOCK,W(4),W1(4)
      DOUBLE PRECISION P,PP
      COMMON P(6,6,6,6)
C     PROGRAM CONTROL
      COMMON DFSTOP,I1,I2,I3,I4
C     LOGICAL UNIT NUMBERS
      COMMON ITTI,ITTO,ILP,IDB,IF1,IF2,IF3
C     EFFORTS
      INTEGER F(6,6,6,6),FF(6,6,6,6)
      COMMON F,FF
C     FLAGS
      COMMON NOQUER
C
      DIMENSION FNAME1(9),FNAME2(9),PP(6,6,6,6)
      DATA ITTI,ITTO,ILP,IDB,IF1,IF2,IF3/5,7,6,8,15,16,17/
      DATA IYES,INO/1HY,1HN/
      DATA NGRID,NSTATE/6,4/
      DATA FF/1296*0/
      DATA IDFFLG /0/
C
      INTEGER F1
      EXTERNAL PROFIT
C     INPUT PARAMETER VALUES
 100  WRITE(ITTO,1000)
 1000 FORMAT(' ARE PARAMETERS FROM FILE (Y OR N)?',/)
      READ (ITTI,1001)I
 1001 FORMAT(A1)
      IF(I-IYES)110,150,110
 110  IF(I-INO)100,120,100
C     INPUT FROM TT
 120  IN=ITTI
      NOQUER=1
      GO TO 160
C     INPUT FROM FILE
 150  WRITE(ITTO,1002)
 1002 FORMAT(' FILE NAME?',/)
      CALL ASSIGN(IF1,FNAME1,-1)
      IN=IF1
      NOQUER=2
 160  WRITE (ITTO,1003)
 1003 FORMAT(' PARAMETER OUTPUT FILE?',/)
      CALL ASSIGN(IF2,FNAME2,-1)
C     PARAMETER INPUT AND OUTPUT
C
      GO TO (170,180),NOQUER
 170  WRITE(ITTO,1004)
 1004 FORMAT(' FECUNDITY, DEATH, AND SELECTIVITY AT EACH AGE',
     1 /,' ONE AGE GROUP PER LINE')
```

```
180   DO 190 I=1,NSTATE
      READ(IN,1005)FECNDY(I),DEATH(I),SELECT(I)
1005  FORMAT(20F12.0)
      WRITE(IF2,1006)FECNDY(I),DEATH(I),SELECT(I)
1006  FORMAT(20E12.4)
190   CONTINUE
      GOTO (200,210),NOQUER
200   WRITE(ITTO,1007)
1007  FORMAT(' NUMBER OF DT VALUES, DTMIN, AND DT GRID SIZE?')
210   READ(IN,1008)NDT,DTMIN,DDT
1008  FORMAT(I12,3E12.4)
      WRITE(IF2,1008)NDT,DTMIN,DDT
      GO TO(220,230),NOQUER
220   WRITE(ITTO,1009)
1009  FORMAT(' P(DT) VALUES, ONE PER LINE')
230   DO 240 I=1,NDT
      READ(IN,1005)PDT(I)
240   WRITE(IF2,1006)PDT(I)
      GOTO (250,260),NOQUER
250   WRITE(ITTO,1010)
1010  FORMAT(' NUMBER OF HARVEST INTENSITIES,',
      1 ' MIN INTENSITY, AND GRID SIZE')
260   READ(IN,1008)NF,FMIN,DF
      WRITE(IF2,1008)NF,FMIN,DF
      GO TO (270,280),NOQUER
270   WRITE(ITTO,1011)
1011  FORMAT(' MAX NUM. OF STAGES, STOPPING PARAM., AND DIS.
 RT.?')
280   READ(IN,1008)NSTAGE,DFSTOP,DSCNT
      WRITE(IF2,1008)NSTAGE,DFSTOP,DSCNT
      GO TO (290,300),NOQUER
290   WRITE(ITTO,1012)
1012  FORMAT(' GRID DENSITY FOR EACH AGE GROUP')
300   READ(IN,1005)(DW(I),I=1,NSTATE)
      WRITE(IF2,1006)(DW(I),I=1,NSTATE)
      GOTO (305,310)  ,NOQUER
305   WRITE(ITTO,1013)
1013  FORMAT(' DESIRED HARVEST')
310   READ(IN,1005) DESHAR
      WRITE (IF2,1006) DESHAR
C     PARAMETER INPUT COMPLETE
C     INITIALIZE PROFIT ARRAY
      DO 311 I4=1,NGRID
      DO 311 I3=1,NGRID
      DO 311 I2=1,NGRID
      DO 311 I1=1,NGRID
311   P(I1,I2,I3,I4)=-DESHAR*DESHAR
C
C     OPEN OUTPUT FILES
      CALL CLOSE(IF1)
      CALL CLOSE(IF2)
      WRITE(ITTO,1015)
1015  FORMAT(' OUTPUT FILE NAMES?',/)
C     IF3 AND IF2 ALTERNATELY CONTAIN ISTAGE VALUES
      CALL ASSIGN(IF3,FNAME2,-1)
```

```
      CALL ASSIGN(IF2,FNAME1,-1)
C
C     CALCULATE GRID SIZE
C     DW(1)=YEMAX/(NGRID-1)
CC    CALCULATE GRID FOR OTHER AGES
C     DO 350 I=2,NSTATE
C     YEMAX=YEMAX*EXP(-DEATH(I-1))
C350  DW(I)=YEMAX/(NGRID-1)
CC    FOR FINAL AGE GROUP USE SUM OF GEOMETRIC SERIES TO
CC           INCREASE THE UPPER BOUND
C     YEMAX=YEMAX/(1.-EXP(-DEATH(NSTATE)))
C     DW(NSTATE)=YEMAX/(NGRID-1)
CC    OUTPUT GRID
C     WRITE(IDB,1013)
C1013 FORMAT(' STATE  GRID')
C     DO 360 I=1,NSTATE
C360  WRITE(IDB,1014)I,DW(I)
C1014 FORMAT(1X,I3,4X,E12.4)
C
C     DYNAMIC OPT.
      DO 500 ISTAGE=1,NSTAGE
      WRITE(IF3,1008)ISTAGE
      F1=0
C     NSTATE DO LOOPS FOLLOW
      DO 384 I4=1,NGRID
      W(4)=DW(4)*(I4-1)
      DO 383 I3=1,NGRID
      W(3)=DW(3)*(I3-1)
      DO 382 I2=1,NGRID
      W(2)=DW(2)*(I2-1)
      DO 381 I1=1,NGRID
      W(1)=DW(1)*(I1-1)
      CALL MAX(PROFIT,P1,F1)
      PP(I1,I2,I3,I4)=P1
      F(I1,I2,I3,I4)=F1
381   CONTINUE
C     OUTPUT P AND F TO OUTPUT FILE
      WRITE(IF3,1006)(PP(I1,I2,I3,I4),I1=1,NGRID)
      WRITE(IF3,1016)(F(I1,I2,I3,I4),I1=1,NGRID)
1016  FORMAT(1X,'"',6I2,'"')
C     SET INITIAL GUESS FOR F
382   F1=F(1,I2,I3,I4)
383   F1=F(1,1,I3,I4)
384   F1=F(1,1,1,I4)
C     STAGE OPT. COMPLETE
C
C     CALC CHANGE IN F, RESET FF TO PRESENT F VALUES
C     NSTATE DO LOOPS FOLLOW
      DF2=0.
      DO 390 I4=1,NGRID
      DO 390 I3=1,NGRID
      DO 390 I2=1,NGRID
      DO 390 I1=1,NGRID
C UPDATE PROFIT ARRAY
      P(I1,I2,I3,I4)=PP(I1,I2,I3,I4)
```

```
      DFR=F(I1,I2,I3,I4)-FF(I1,I2,I3,I4)
      DF2=DF2+DFR*DFR
390   FF(I1,I2,I3,I4)=F(I1,I2,I3,I4)
      WRITE(IDB,1017)ISTAGE,DF2
1017  FORMAT(' STAGE',I3,'  COMPLETE',/,' DF2=',E12.4)
C
C     EXCHANGE OUTPUT FILES
      IFH=IF3
      IF3=IF2
      IF2=IFH
      REWIND IF3
      IF(DF2-DFSTOP)490,490,500
490   IF(IDFFLG.EQ.1) GO TO 550
      IDFFLG=1
500   CONTINUE
C
550   CONTINUE
      CALL CLOSE(IF2)
      CALL CLOSE(IF3)
      STOP
      END
      SUBROUTINE MAX(FUNC,VALU,CONTRL)
C     MAX THE FUNCTION FUNC OVER CONTROLS
C     CONTRL IS THE INITIAL GUESS OF THE OPTIMUM CONTROL
C     VALU IS THE OPTIMUM VALUE OF FUNC
C
      EXTERNAL FUNC
      INTEGER CONTRL,C
C     PARAMETERS
      COMMON FECNDY(4),DEATH(4),SELECT(4)
      COMMON PDT(20),NDT,DDT,DTMIN,NSTATE,NSTAGE,NGRID
      COMMON FMIN,DF,NF
      COMMON DSCNT, DESHAR
C     OUTPUTS
      COMMON DW(4),STOCK,W(4),W1(4)
      DOUBLE PRECISION P
      COMMON P(6,6,6,6)
C     PROGRAM CONTROL
      COMMON DFSTOP,I1,I2,I3,I4
C     LOGICAL UNIT NUMBERS
      COMMON ITTI,ITTO,ILP,IDB,IF1,IF2,IF3
C     EFFORTS
      INTEGER F,FF
      COMMON F(6,6,6,6),FF(6,6,6;6)
C     FLAGS
      COMMON NOQUER
C
C
C
      C=CONTRL
      V1=FUNC(C)
      V2=FUNC(C+1)
      IF(V2-V1)50,100,10
C     LOOK FOR LARGER VALUE OF F
10    IF(C-NF)20,50,50
```

```
20     C=C+1
       V1=V2
       V2=FUNC(C+1)
       IF(V2-V1)30,30,10
30     V2=V1
       GO TO 100
C      LOOK FOR SMALLER VALUE OF F
50     IF(C)100,100,60
60     V2=V1
       C=C-1
       V1=FUNC(C)
       IF(V2-V1)50,100,100
100    CONTRL=C
       VALU=V2
       RETURN
       END
       FUNCTION PROFIT(F1)
       INTEGER F1
C      PARAMETERS
       COMMON FECNDY(4),DEATH(4),SELECT(4)
       COMMON PDT(20),NDT,DDT,DTMIN,NSTATE,NSTAGE,NGRID
       COMMON FMIN,DF,NF
       COMMON DSCNT, DESHAR
C      OUTPUTS
       COMMON DW(4),STOCK,W(4),W1(4)
       DOUBLE PRECISION P
       COMMON P(6,6,6,6)
C      PROGRAM CONTROL
       COMMON DFSTOP,I1,I2,I3,I4
C      LOGICAL UNIT NUMBERS
       COMMON ITTI,ITTO,ILP,IDB,IF1,IF2,IF3
C      EFFORTS
       INTEGER F,FF
       COMMON F(6,6,6,6),FF(6,6,6,6)
C      FLAGS
       COMMON NOQUER
C
       PROFIT=0.
       CALL DEATHC(F1,H)
       H=-(H-DESHAR)**2
       DO 20 I=1,NDT
       DT=DTMIN+(I-1)*DDT
       W1(1)=RECRUT(DT)
20     PROFIT=PROFIT+PDT(I)*(H+VALUE(W1)*DSCNT)
       RETURN
       END
       SUBROUTINE DEATHC(F1,H)
       INTEGER F1
C      PARAMETERS
       COMMON FECNDY(4),DEATH(4),SELECT(4)
       COMMON PDT(20),NDT,DDT,DTMIN,NSTATE,NSTAGE,NGRID
       COMMON FMIN,DF,NF
       COMMON DSCNT, DESHAR
C      OUTPUTS
       COMMON DW(4),STOCK,W(4),W1(4)
```

APPENDIX A.
FORTRAN Code for SDP Algorithm

```
      DOUBLE PRECISION P
      COMMON P(6,6,6,6)
C     PROGRAM CONTROL
      COMMON DFSTOP,I1,I2,I3,I4
C     LOGICAL UNIT NUMBERS
      COMMON ITTI,ITTO,ILP,IDB,IF1,IF2,IF3
C     EFFORTS
      INTEGER F,FF
      COMMON F(6,6,6,6),FF(6,6,6,6)
C     FLAGS
      COMMON NOQUER
C
      FR=FMIN+F1*DF
C
      H=0.
      DO 10 I=2,NSTATE
      II=I-1
      CATCH=FR*SELECT(II)
      SURV=W(II)*EXP(-CATCH-DEATH(II))
      DEAD=W(II)-SURV
      H=H+DEAD*CATCH/(CATCH+DEATH(II))
 10   W1(I)=SURV
C     DEATH OF FISH NSTATE YEARS AND OLDER
      CATCH=FR*SELECT(NSTATE)
      SURV=W(NSTATE)*EXP(-CATCH-DEATH(NSTATE))
      DEAD=W(NSTATE)-SURV
      H=H+DEAD*CATCH/(CATCH+DEATH(NSTATE))
      W1(NSTATE)=W1(NSTATE)+SURV
      RETURN
      END
      FUNCTION RECRUT(DT)
C     PARAMETERS
      COMMON FECNDY(4),DEATH(4),SELECT(4)
      COMMON PDT(20),NDT,DDT,DTMIN,NSTATE,NSTAGE,NGRID
      COMMON FMIN,DF,NF
      COMMON DSCNT, DESHAR
C     OUTPUTS
      COMMON DW(4),STOCK,W(4),W1(4)
      DOUBLE PRECISION P
      COMMON P(6,6,6,6)
C     PROGRAM CONTROL
      COMMON DFSTOP,I1,I2,I3,I4
C     LOGICAL UNIT NUMBERS
      COMMON ITTI,ITTO,ILP,IDB,IF1,IF2,IF3
C     EFFORTS
      INTEGER F,FF
      COMMON F(6,6,6,6),FF(6,6,6,6)
C     FLAGS
      COMMON NOQUER
C
C
      STOCK=FECNDY(1)*W(1)
      DO 10 I=2,NSTATE
 10   STOCK=STOCK+FECNDY(I)*W(I)
C STOCK INDEX IS MILLIONS OF FISH THUS FOLLOWING MODIFICATION
```

```
      STOCK=STOCK/1.0E6
      RECRUT=0.2828*STOCK*EXP(-0.284*STOCK+11.99*DT)
      RECRUT=RECRUT*1.0E6
      RETURN
      END
      FUNCTION VALUE(W2)
      DIMENSION W2(4),J(4),DW1(4)
C     PARAMETERS
      COMMON FECNDY(4),DEATH(4),SELECT(4)
      COMMON PDT(20),NDT,DDT,DTMIN,NSTATE,NSTAGE,NGRID
      COMMON FMIN,DF,NF
      COMMON DSCNT, DESHAR
C     OUTPUTS
      COMMON DW(4),STOCK,W(4),W1(4)
      DOUBLE PRECISION P
      COMMON P(6,6,6,6)
C     PROGRAM CONTROL
      COMMON DFSTOP,I1,I2,I3,I4
C     LOGICAL UNIT NUMBERS
      COMMON ITTI,ITTO,ILP,IDB,IF1,IF2,IF3
C     EFFORTS
      INTEGER F,FF
      COMMON F(6,6,6,6),FF(6,6,6,6)
C     FLAGS
      COMMON NOQUER
C
C
C     INTERPOLATION OF FUTURE VALUE
      DO 10 I=1,NSTATE
      J(I)=W2(I)/DW(I)+1.
      IF(J(I).LT.NGRID)GO TO 5
      J(I)=NGRID-1
5     DW1(I)=W2(I)-(J(I)-1)*DW(I)
      IF (DW1(I).GT.DW(I)) DW1(I)=DW(I)
 10   CONTINUE
      PI=P(J(1),J(2),J(3),J(4))
      VALUE=PI
D     WRITE(ITTO,100)W2,DW,DW1,VALUE,J
D100  FORMAT(3(1X,4G15.5,/),1X,G15.5,4I10)
      DO 20 I=1,NSTATE
      J(I)=J(I)+1
      DPI=P(J(1),J(2),J(3),J(4))-PI
D     WRITE(ITTO,100)DPI
      VALUE=VALUE+(DPI/DW(I))*DW1(I)
 20   J(I)=J(I)-1
      RETURN
      END
```