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Optimal Resource Management under Conditions of Uncertainty: The Case of an Ocean Fishery

A dissertation submitted in partial satisfaction of the requirements for the degree Doctor of Philosophy in Economics

by

Tracy Royal Lewis

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1975

The dissertation of Tracy Royal Lewis is approved and it is acceptable in quality and form for publication on microfilm:

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ABSTRACT OF THE DISSERTATION

Optimal Resource Management under Conditions of Uncertainty: The Case of an Ocean Fishery

by

Tracy Royal Lewis

Doctor of Philosophy in Economics

University of California, San Diego, 1975

Professor Richard Schmalensee, Chairman

A Markov Decision Process model is developed for analyzing the socially optimal allocation of a replenishable or non replenishable resource over time. The resource is managed by choosing the rate of extraction in each period to maximize the discounted stream of expected social returns. Elements of uncertainty enter the analysis in three ways: (1) Uncertainties may exist about the current size of the resource, either because of difficulties in observing the stock, as in the case of a fishery, or because of the possibilities of finding new reserves through exploration, as in the case of minerals and oil. (2) The market value of the resource and the cost of extracting it may be random, due to varying

economic conditions. (3) Unpredictable changes in the environment may perturb the natural rate of growth or deterioration of the resource, as well as the effective rate of depletion by man.

The model is used to answer these questions: How do optimal programs for allocating resources in a deterministic environment compare with optimal programs under stochastic conditions? Do different attitudes toward social risk bearing as regards variations in resource rents, have an effect on optimal decision rules? What is the effect of increased uncertainty about resource prices, extraction costs, and resource growth and depletion rates on optimal programs?

The questions posed above are considered in the context of an empirical study of the Eastern Pacific yellowfin tuna fishery. The main conclusions of the study are that: (1) Optimal programs for resource management are more moderate, with smaller variations in the rate of fishing over time, when society is risk averse rather than risk neutral. This difference betweeen risk neutral and risk averse programs is accentuated with increasing uncertainty about market prices, fishing costs, and the future availability of the resource. (2) "Cyclical" fishing, in which the stock is depleted rapidly over a short time period and then allowed to grow back, is optimal if scale economies exist in the fishing industry. This contrasts with the optimal "steady state" fishing programs that are emphasized in the control theory literature on resource management.

Chapter I

INTRODUCTION

A. INTRODUCTION AND REVIEW OF LITERATURE

The ongoing concern over natural resources has peaked recently with the emergence of possible world wide shortages of energy and food. Extrapolating on current growth trends in population and resource depletion, the now famous Club of Rome studies[1] predict a sudden and uncontrollable decline in world population and living standards unless these trends are quickly reversed. Of course, this is not the first warning of Mathusian doom, nor are the conclusions from these studies universally accepted. A more optimistic view of the future espoused by Nordhaus (1974) and Smith (1974) is that as some of the valuable nonreplenishable resources become scarce society will find substitutes for them. For example, solar radiation is a substitute source of energy for fossil fuels, and it appears to be virtually inexhaustible.

Probably most economists would agree that the world will survive in spite of the finite supply of natural resources. Yet, there are numerous technical and socio-economic problems still to be solved in the quest for optimal resource utilization. The most basic problem has been to identify a common set of objectives for resource management. This is particularly difficult for marine resources such as fisheries and oil and mineral deposits found in

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[1] See footnotes on page 14.

the ocean that are owned and used jointly by different countries.[2] Typically, these countries have disparate social value systems, and different preferences for present versus future consumption of the resource. Common agreement on principles of resource management is not easy to obtain when national economies are organized according to different ideologies as in the case of developed and underdeveloped countries or socialist and capitalist nations.

The common property characteristic of ocean fisheries, various wild animal populations, and certain common underground oil pools presents a special problem. No single user has exclusive property rights to these resource stocks, nor can he prevent others from sharing in its exploitation. Thus, the individual is in competition with all others in an attempt to appropriate a large portion of the stock for himself. Efforts by one user to conserve the resource will be futile, since there is no guarantee that others will do the same. Consequently, the stock is depleted rapidly until further extraction is not economical. To prevent over use of the resource, quotas, extraction taxes, and licensing shcemes are sometimes introduced. Unfortunately, such programs are difficult to institute and enforce since they require the cooperation of all independent resource consumers.

It appears that resources with well defined property rights might offer a welcome relief from the aforementioned common property situation. This is not true, however, if ownership is concentrated among only a few individuals, thus creating a potential oligopoly market in resources. For example, the majority of current and future world reserves of oil are controlled by a small number of countries in the Middle East. In recognition of their potential bargaining power these countries have formed an oil cartel known as the Organization of Petroleum Exporting Countries. As a result, since 1970 when the Organization began to assert itself in the petroleum market, the price of Middle East light crude has increased by about five-hundred percent.[3]

It would be naive and presumptuous to suggest that these problems are soluble through economic analysis alone. Only an interdisciplinary program enlisting the expertise from various social and physical sciences will contribute to their resolution. Economists can help by describing the resource extraction patterns under varying conditions. For example, it is generally known that resource use differs according to whether markets are competitive or monopolistic and that neither of these market forms will necessarily produce the socially optimal scheme for resource exploitation.[4] By evaluating resource allocation under different sets of political, social, and institutional constraints, economists can identify those extraction programs most consistent with national goals, as well as suggest the tradeoffs between attaining certain political and economic objectives. Probably, however, economists have been most productive in specifying optimal models of resource use--optimal in the sense of maximizing certain efficiency criteria. Although efficiency is not the only dimension of resource valuation,[5] these models are a useful reference for constructing new effective management programs and evaluating those already in existence.

The extensive literature on the economics of optimal resource management is separated naturally into two divisions according to whether the resource is nonrenewable or renewable. The first formal analysis of nonrenewable resources, sometimes referred to as the Theory of the Mine, was presented by Hotelling (1931). Following Hotelling's analysis, Gordon (1967), Herfindahl (1967), Scott (1967), and Cummings (1969) have considered optimal resource extraction from the point of view of an individual firm. Recently, public interest centering on the effects of resource shortages on economic growth has prompted a new body of literature, particularly the works by Anderson (1972), Vousden (1973), Smith (1974), and Schmalensee et al. (1975). These authors are concerned with the problems of resource constrained optimal economic growth. Special attention is paid to analyzing the time horizon over which resource exhaustion occurs and the resulting pattern of extraction.

Unlike the Theory of the Mine, the potential for resource growth is important in the analysis of renewable resources. Primary emphasis in the literature has been on the optimal use of resources in commercial ocean fisheries. The earliest works on this subject by Gordon (1954), Scott (1955), Turvey (1964), Christy and Scott (1965), Crutchfield and Pontecorvo (1969), and Smith (1969) consider static models in which the rate of fish landings is chosen to maximize the net economic yield from the fishery while keeping the stock in biological equilibrium.[6] Although these studies abstract from the dynamic characteristics of the fishery, they are important in emphasizing and formalizing the idea that competitive harvesting of a common property resource is inefficient unless it is owned or managed by one party.

In the current stage of economic modelling of the fishery Crutchfield and Zellner (1962), Plourde (1970) and (1971), Quirk and Smith (1970), Clark (1973), Brown (1974), Neher (1974), and Spence (1973) extend previous analyses by providing an explicit dynamic treatment of optimal resource use. These authors employ optimal control theory[7] in choosing the rate of fish landings in each time period to maximize the sum of discounted rents, subject to changes in the population caused by natural growth and mortality, and predation by man. Some interesting suggestions for coping with the stock-flow dynamics of the fishery have evolved from these studies.

B. PURPOSE OF THE STUDY

The aforementioned analyses assume a deterministic world in which all current and future demands, prices, and costs are known, in which the current reserve of the resource can be observed and measured exactly, in which environmental factors affecting the growth or deterioration of the resource are either unimportant or are perfectly predictable, and in which the entire time path of reserves and extraction rates can be calculated with certainty for a given program of resource management. In reality, of course, there is not only uncertainty regarding current and future resource prices, as well as the effects of environmental changes on resource stocks, but also there is often uncertainty about the existing supply of the resource available for extraction. Deterministic models have dominated the literature thus far not because the elements of uncertainty are unimportant or because they have gone unrecognized,[8] but because existing stochastic models are either not operable or too difficult to work with. Unfortunately, by neglecting the effects of uncertainty in analyzing and advocating optimal programs for resource management, economists have done little to inspire public confidence in current resource conservation efforts. The purpose of this study is to mitigate some of the deficiencies in the literature by introducing and analyzing a general model of resource management that readily incorporates various aspects of uncertainty.

B.1. Description of the Model

In our model the resource, whether it be a fishery, a mineral deposit, an oil reserve, etc., is controlled by a hypothetical social manager. It is assumed that the manager chooses the rate of extraction in each period to maximize the expected social utility of the stream of economic rents from the resource. Although we are interested in socially optimal behavior, the model is also appropriate for describing resource use for different market and allocation systems. Elements of uncertainty are accommodated in the analysis in the following forms: (1) Uncertainties may exist about the current size of the resource either because of difficulties in observing and measuring the resource stock, as in the case of fisheries, or because of the possibilities of finding new reserves through exploration, as in the case of minerals and oil; (2) the market price of the resource may vary due to fluctuations in consumer demand and the availability of substitutes. The costs of extracting the resource may also be random; (3) unpredictable changes in th environment may perturb the natural rate of growth or deterioration of the resource as well as the effective rate of depletion by man. For example, variations in the weather and the temperature of the water may have an effect on the natural growth rate of a fish population and the rate at which the fish are caught.

The optimizing technique for this analysis, developed by Howard (1960) is an application of dynamic programming to a discrete

Markov process model. The dynamic structure of the resource extraction program is described in terms of a simple, one period Markov process model with a finite number of states. In its most basic scalor form a state is simply a possible size of the resource stock; in more complicated vector forms a state might contain information on the size of the stock, the season of the year, prevailing economic and political conditions, etc. During a particular time interval, the program is in a certain state if it is described by the value of all the variables that define the state. A state transition occurs when its describing variables change from the values specified for one state to those specified for another. Movements from one state to another, described by the transition probabilities are random as a result of variations in environmental and socio-economic conditions affecting the natural growth and depletion of the resource. Thus, the transition probabilities in the simplest scalor form depend on the growth of the stock (which is important in the case of renewable resources), and on the rate of extraction.

With the states and transition probabilities fully specified, the manager regulates the use of the resource over time to maximize the expected social utility of the stream of future rents from the reserve. It is assumed that there are a finite number of possible extraction rates in each period for the manager to select from. This type of formulation results in a sequential optimization problem that is solved by dynamic programming.

The most important feature of this programming approach is the ease with which elements of uncertainty are incorporated into the model. Stochastic elements are not accommodated at all in the control theory models used in the literature. In addition, there are no restrictions on the form of the criterion function and the equation of motion of the state variables imposed by the Markov model. This enables one to analyze cases where the functions are not concave, a condition usually needed in control theory problems,[9] and where the criterion function is not quadratic, a necessary condition to invoke "certainty equivalence" theory.[10] For example, cases of scale economies that are usually ignored because they give rise to non-concave criterion functions are easily included in the Markov decision model.

Another attractive feature of our model is the relative ease of solution by computer. In contrast to control theory analyses which generally only provide conditions for optimality, the programming method yields complete solutions to the allocation problem. In addition, explicit calculations of the expected present value for different allocations strategies are obtained.

B.2. Analysis of the Model

Once formulated and tested, the model is used to study the effects of uncertainty on optimal decision rules for the allocation of natural resources over time. In particular, we focus on the following questions: How do optimal programs for allocating resources in a deterministic environment compare with optimal programs derived under stochastic conditions? Do deterministic decision rules serve as a good approximation for optimal stochastic programs? How do different attitudes for risk bearing with regards to variations in resource rents effect optimal decision rules? Is the usual practice of representing the "riskiness" of a project in terms of the social discount rate appropriate for use in stochastic sequential maximization problems such as ours? What is the affect of increased uncertainty about consumer demand, and resource growth and depletion rates on optimal programs?

Following a general specification of the Markov model in Chapter II, an analysis of the questions posed above are applied to a study of a specific renewable resource, the Eastern Pacific yellowfin tuna fishery. Because the resource can replenish itself, models of renewable resources generally are more complex than models of nonrenewable resources. Thus, although the study pertains to fisheries, our model is easily modified for analyzing nonrenewable resource problems.

Apart from demonstrating the use of our model, the purpose of this study is to generate some practical policy recommendations for the management of the Eastern Pacific yellowfin tuna fishery. The fishery is not only important as a food source, but it also provides incomes for fishermen from the United States, Canada, Japan, and several South and Central American countries. The data on the fishery needed for implementing the model will be matched against that which is currently available. Where data are lacking, a sensitivity analysis on various parameters is undertaken to identify areas requiring further empirical research.

C. PLAN OF THE STUDY

In Chapter II the optimal allocation of a natural resource is described in general form in terms of a finite state and action Markovian decision process. First, changes in the resource stock as a function of natural growth (for replenishable resources) and depletion are specified. Various maximization criteria are examined, and the resource allocation problem is formulated as a discrete dynamic programming problem. It is seen that a solution to this problem exists and Howard's algorithm for finding it is presented. Certain limitations of the model are discussed and suggestions for extensions are made.

In Chapter III the economic and biological characteristics of the Eastern Pacific yellowfin tuna fishery are modelled in terms of a discrete Markov system. Assuming deterministic conditions, the allocation problem for this fishery is formulated and solved by the programming procedures introduced in Chapter II. The general form of the optimal strategy is examined and summarized for use later on in comparison with optimal stochastic decision rules. Solutions to this problem are also derived by optimal control methods as an accuracy check for the Markov decision model.

A probabilistic model of the tuna fishery allowing for variations in consumer demand and uncertainty about population growth and depletion rates is presented and solved in Chapter IV. The resulting optimal stochastic strategies are compared with deterministic decision rules. We find that in certain cases policies for resource consumption derived for deterministic conditions are also appropriate in a stochastic environment. The effects of increasing uncertainty in consumer demand and population growth rates on optimal allocation programs are assessed. Different attitudes for risk bearing are analyzed for their impact on optimal programs, and the prospects for being able to represent risk via the discount rate are examined. Finally, areas requiring additional empirical research are identified.

Footnotes

[1] See Meadows et al. (1972) and Forrester (1971).

[2] For a discussion of the problems involved in managing internationally owned resources, see Crutchfield (1972).

[3] For a discussion of the economic implications of the formation of the Organization of Petroleum Exporting Countries, see Schmalensee et al. (1975).

[4] On this point see Burt and Cummings (1969), Hotelling (1931), Lewis (1974), Smith (1968), and Solow (1974).

[5] Other goals that might influence a country's use of the resource would be reducing unemployment and attaining a favorable balance of payments situation.

[6] This is analogous to finding the "Golden Rule" in standard models of capital accumulation.

[7] In this context the term "optimal control theory" includes both the Pontryagin Maximum Principle, and the Calculus of Variations optimization methods.

[8] For example, see the discussion by Scott (1967, p.26).

[9] See Kamien and Schwartz (1971).

[10] See Holt et al. (1960).

Chapter II

MARKOV DECISION PROCESS MODEL

In this chapter the problem of allocating a renewable or non-renewable natural resource over time to maximize net economic returns is described in general terms in the form of a finite state and action Markovian decision process. The basic model we introduce allows for the important effects of environmental variation on the natural growth and depletion of the resource and the effect of random changes in socio-economic conditions on market prices and the costs of extraction. This model is subsequently used in Chapters III and IV to analyze the Eastern Pacific yellowfin tuna fishery.

The plan of the chapter is as follows: Changes in the resource stock caused by the natural growth or deterioration of the stock as well as the depletion due to man are specified in section A. Various criteria for allocating the resource over time, that depend on the social attitudes toward risk, are set forth in section B. In section C a discrete dynamic programming approach is formulated for analyzing the resource allocation problem. It is seen that a solution exists and Howard's algorithm[1] for finding it is presented. In section D the basic model is modified and extended in various ways to allow for (1) seasonal variation in market prices, extraction costs and resource growth (in the case of fisheries), (2) a non stationary stochastic process caused by temporal changes in certain parameter distributions, (3) the possibility of joint resource management, as in the case of two interacting fish populations, or two price or cost

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[1] See footnotes on pages 47-48.

related mineral reserves, and (4) errors in observing and measuring the actual size of the resource pool available for exploitation.

A. GROWTH CHARACTERISTICS OF THE RESOURCE

In each time interval, the rate of change in the resource reserve depends on the rate of natural growth of the stock and the rate of depletion by man. Thus,

$$X_{t+1} = X_t + f(X_t) - L_t \tag{1}$$

where: X_t = resource stock at time t

L_t = rate of extraction at time t

$f(X_t)$ = a function that measures changes in the stock due to natural growth or deterioration of the resource.

Equation (1) states that the available stock at time $t+1$ equals the stock at time t enhanced by the rate of growth of the resource during that period minus the rate of extraction. The model is easily modified for the case of petroleum reserves where very large values of L_t result in more than proportional drops in recoverable resources due to water seepage effects.[2]

Normally, we assume $f(X_t) = 0$ for nonrenewable resources, although nearly all minerals, natural gases and oils, generally conceived of being fixed in supply, are replenishable over a time span of millions of years. On the other hand, some resources such as uranium, depreciate or deteriorate over time so that $f(X_t) < 0$. For renewable resources, $f(X_t)$ is the natural growth function indicating the rate of resource replenishment. In Chapter III the form of $f(X_t)$ is specified in greater detail as it pertains to a fishery population.

Defining E_t as a composite input variable representing the capital and labor used in resource extraction at time t,

$$L_t = g(X_t, E_t) \tag{2}$$

where $g(\ )$ is a production function for extraction. The stock X_t enters production essentially as a capital input, which when combined with the variable input E_t yields a flow of resource consumption. For most resources we assume

$$\frac{\partial g}{\partial X} \geq 0 \ ; \ \frac{\partial}{\partial X}\frac{\partial g}{\partial E} \geq 0 \tag{3}$$

reflecting the increased difficulty of harvesting or extracting the resource as it becomes more scarce. Obvious examples of this occur in fisheries where catch rates decline (for given E_t) with smaller populations since the fish are harder to locate, and in mining where extraction decreases because lower grade ores are encountered as the resource is depleted. Of course, it is possible that the size of the resource reserve has no marginal effect on production in which case L_t is a function of E_t only,[3] although we shall retain the more general specification of L_t in equation (2).

Allowing for uncertainty in resource growth and depletion rates, and substituting for L_t from equation (2), we obtain

$$X_{t+1} = X_t + \eta_{1t} f(X_t) - \eta_{2t} g(X_t, E_t) \qquad (4)$$

where η_{1t} and η_{2t} are random variables. To illustrate the meaning of equation (4), in the context of ocean fisheries, η_{1t} might represent random changes in the natural rate of growth and η_{2t} might measure variations in the depletion rate of the resource caused by random changes in the water temperature and weather conditions. In terms of mineral and petroleum resources, η_{2t} might describe the effect on extraction rates for varying mining and drilling conditions. For the present, we assume the distributions for η_{1t} and η_{2t} are stationary through time with expected values, $\mathcal{E}(\eta_{1t}) = \mathcal{E}(\eta_{2t}) = 1$. Thus the expected value of X_{t+1} in equation (4) is equal to its value under deterministic conditions given by equation (1). In section D our model is modified to allow for temporal changes in the distributions for η_{1t} and η_{2t}, perhaps as a result of seasonal variation in environmental conditions. Naturally, random disturbances in the resource reserve need not enter multiplicatively as in equation (4); however we retain this form for use later on in analyzing the fishery.

For a given initial stock size, equation (4) specifies which programs of resource extraction are feasible. In turn, the next section examines several criteria for selecting the best of these feasible programs.

B. CRITERIA FOR OPTIMAL RESOURCE ALLOCATION

In the present literature on resource economics, a certain or riskless world is assumed in which all physical and economic processes are deterministic. According to this analysis, the criteria for optimal resource allocation is to maximize the present value, V, of the certain stream of economic rents from the resource over time, represented by

$$V = \sum_{t=0}^{\infty} B^t R_t \; ; \qquad B = \frac{1}{1+\rho} \tag{5}$$

The economic rent,[4] R(t), is taken as a measure of the net benefit to society from the consumption of the resource. The distribution of the rent is not considered, presumably because a larger total rent can in principle be redistributed so as to make everyone better off than in a situation with a smaller aggregate rent.[5] The stream of rents is discounted at the rate of ρ, which is the social rate of time discount. Assuming efficiency throughout the economy, ρ is the rate of return on private riskless investments.

In reality, however, our physical, political, and economic environment is dominated by risk and uncertainty. There is uncertainty about locating the resource, an important consideration for petroleum reserves and ocean fisheries, and about the costs of extraction. Sudden social and economic changes throughout the world cause fluctuations in the market price of natural resources as we have witnessed recently with respect to the price of gold and petroleum products. This means that the economic rent from the resource use is a random variable whose distribution is determined by a combination of stochastic social, economic, and physical processes. Under these circumstances, the objective of maximizing present value in equation (5) is not meaningful, and the question arises as to what is an acceptable criterion for the allocation of natural resources over time. This is not a trivial consideration since the welfare of many countries and many individuals depends directly on the receipts from natural resource production. Consideration of this question is best handled by first examining possible attitudes toward risk, and second by representing these attitudes in some analytical or functional form.

B.1. Attitudes Toward Risk

The net social benefit from the use of a natural resource will depend on society's risk attitude toward variability in economic yields. The approach taken in this paper is that the risk attitude of individuals is important in determining risk preferences of society. It is generally accepted that individuals are not indifferent to risk and that investors must be paid a "risk premium" yield above the expected rate of return as compensation for the costs of risk-bearing. For example in marine fisheries, risk averse behavior serves to explain the prevalence of share contracting[6] between boat owners and fishermen.

Following the arguments of Cheung (1969), Reid (1974), Stiglitz (1974), and Sutinen (1973) share contracts may be regarded as a device for risk sharing--in this case the variance of the fishery yield is distributed among the contracting parties. Assuming risk aversion, it can be shown that a share contract will be mutually preferred by the boat owner and fishermen.[7]

Accepting the fact that private risk aversion exists, the major issue with respect to evaluating public projects in general and the management of a resource in particular is if the private cost of risk-bearing represents a social cost as well. This question has provoked much controversy in the cost-benefit literature on government investment decisions.[8] The major support for the viewpoint that private risk aversion is socially unimportant stems from the pooling argument due to Samuelson (1964) and Vickrey (1964) and the risk spreading argument due to Arrow and Lind (1970). The pooling argument asserts that the government invests in a large number of diverse projects and is able to pool risks to a much greater extent than the private sector. Although the outcome of any particular investment may be uncertain, the entire investment program taken as a whole is virtually riskless. The risk spreading argument applies to private as well as public investment. Arrow and Lind show that when the risks associated with any project are distributed among a large number of people so that the size of the share born by each individual is a very small component of his income, the total of the costs of risk-bearing is negligible. The inverse of this result implies that even with public projects, significant social costs of risk-bearing may exist when some benefits and costs of sizeable magnitude accrue to individuals, so that these individuals incur the attendant costs of risk-bearing.

With regard to the management of a natural resource the actual distribution of risks and the attendant cost of risk-bearing will depend largely on the structure of the management program. For example, assume that all rents are captured in profits[9] and suppose that the resource is managed by a government control authority which employs private producers at a fixed wage to extract the resource with the resulting profits distributed equally among the taxpayers. Although total profits may vary considerably, the size of the share going to an individual taxpayer is presumably a negligible component of his income and the total cost of risk-bearing can be ignored. Suppose instead that the rents are redistributed to producers in the form of lump sum transfers. Under these circumstances, resource rents of a large magnitude may accrue to a small number of individuals and the social cost of risk-bearing cannot be ignored.

From this section we see that the social attitude towards uncertainty will depend on the structure of the management program and the fashion in which the rents from the resource are distributed. Economists have proposed numerous systems for resource management, including the imposition of taxes and subsidies on resource use, the sale of extraction licenses, and placing direct quotas and limitations on resource production. Each of these schemes results in a different distribution of the economic rents. A general theory of natural resource allocation under uncertainty should allow for averse and neutral attitudes towards risk, depending on the institutional structure of the management program. The next section demonstrates how different attitudes towards risk can be represented in an analytical form that serves as a criterion for maximizing the net social benefit from resource exploitation.

B.2. Maximization Criteria for Different Attitudes Towards Risk

The approach here is to describe the resource allocation problem in terms of the classic Von Neumann-Morgenstern theory of individual decision making under uncertainty. It is assumed that the manager utilizes the resource through time so as to obtain the socially optimal sequence of economic rents R.

$$R = (R_1, R_2, \ldots, R_t, \ldots)$$

where R_t is the economic rent from the resource at time t. Due to various physical and economic uncertainties, the rent sequence is random. Consequently, the manager must select the best of the available probability distributions for R which are called random prospects. If we assume that the manager's behavior in solving this problem conforms to the Von Neumann-Morgenstern axioms,[10] then it can be inferred that the preference ordering for various random prospects can be represented by a utility function

$$U(R) = U(R_1, R_2, \ldots, R_t, \ldots)$$

and that the best prospect is found by maximizing the expected value of utility.

Assuming that U(R) is an additive separable utility function, and that time preference enters in the form of a constant multiplicative discount factor, the certainty equivalence criterion, C.E., can be written as

$$C.E. = \sum_{t=0} B^t \mathcal{E}[U(R_t)]; \quad B = \frac{1}{1+\rho}$$

where ρ is the riskless interest rate and $\mathcal{E}[U(R_t)]$ is the certainty equivalent of the possible economic rents from the resource at time t. The social attitude towards risk in resource rents is represented by the form of $U(R_t)$. Strict concavity in the utility function implies risk aversion, while risk neutrality occurs if $U(R_t)$ is a linear function. For purposes of comparison, different forms of the utility function may be used to analyze the optimal resource allocation. The choice of the particular function is based on its risk characteristic in terms of the measures of absolute and relative risk aversion developed by Arrow (1965) and Pratt (1964).

In taking this approach to resource management, we abstract from several issues which should be mentioned. First, the problems associated with "group decision making" are submerged behind our assumption of a single resource manager who makes allocation decisions for society. Somehow the manager is able to sort out and reconcile different individual objectives and preferences for utilizing the resource in a consistent and equitable manner. Second, in maximizing the expected utility of the stream of rents from the resource we abstract from other possible goals of economic policy such as attaining high employment, acquiring a favorable balance of payments position, etc. While these are important issues pertaining to resource management, a proper treatment of these problems is beyond the scope of this study.

C. DYNAMIC PROGRAMMING FORMULATION

In section A changes in the resource stock caused by natural growth and depletion have been examined. The appropriate criterion for evaluating resource use has been analyzed in section B. What remains then is to develop a decision process for finding the optimal allocation of resources over time.

Assume the resource is described by a finite number of states, each state corresponding to a certain stock size. In each time period, t, the rent from the resource will be a function of the stock at that time, X_t, and the amount of inputs, E_t, which we shall call effort, used in the extraction process. The manager seeks to

$$\underset{E_t}{\text{maximize}} \sum_{t=0}^{N} B^t \mathcal{E}[U(R(E_t, X_t))] \qquad (7)$$

Suppose the resource is in state i with N time periods left in the planning horizon. The manager selects an effort allocation policy, d, from a finite number of possibilities. A policy is a rule for choosing the amount of effort used for extraction in each time period. $V_i^d(N)$ is the expected social value from the resource obtained with policy d given that the resource starts in state i. It is defined by

$$V_i^d(N) = \mathcal{E}\left[\sum_{t=0}^{N} B^t\, U(R(E_t^d,\ X_t^d))/X_0 = X_i\right] \tag{8}$$

It is possible to rewrite equation (8) in recursive form such that

$$V_i^d(N) = q_i^d + B \sum_j p_{i,j}^d\ V_j^d(N-1) \tag{9}$$

where $p_{i,j}^d$ is the transition probability that the stock moves from state i to state j for policy d. The immediate expected social return from the resource is $q_i^d = \mathcal{E}\,U(R(E^d, X_i^d))$. Equation (9) means that the expected social value, $V_i^d(N)$, is equal to the immediate expected return q_i^d plus the sum of the discounted values of being in state j with N - 1 periods left, weighted by the probability that the resource will occupy state j in the next time period. If there are S+1 possible states for the resource, writing equation (9) in matrix form yields

$$V^d(N) = Q^d + BP^d V^d(N-1) \tag{10}$$

where:

$V^d(N)$ is an S+1 dimensional column vector of the $V_i^d(N)$'s

Q^d is an S+1 dimensional column vector of the q_i^d's

P^d is the Markov transition matrix corresponding to policy d; $P^d = [p_{i,j}^d]$; $i,j = 0, 1, 2, 3, \ldots, S$.

C. 1. Steady State Properties, Existence of Solution, and Solution Algorithm

We want to consider a planning horizon of indefinite duration for the resource. Consider equation (10) as the number of periods in the planning horizon becomes large. Assume a particular policy, d, has been selected so that a given Markov process is specified. Dropping the superscript, equation (10) becomes

$$V(N) = Q + BPV(N-1) \tag{11}$$

Writing V(1), V(2), V(3) ... explicitly

$$\begin{aligned} V(1) &= Q + BPV(0) \\ V(2) &= Q + BPQ + B^2P^2V(0) \\ V(3) &= Q + BPQ + B^2P^2Q + B^3P^3V(0) \end{aligned} \tag{12}$$

The general form of these equations is

$$V(N) = \left[\sum_{j=0}^{N-1} (BP)^j \right] Q + B^N P^N V(0) \tag{13}$$

Since $0 \le B < 1$,

$$\lim_{N \to \infty} V(N) = \sum_{j=0}^{\infty} (BP)^j Q \tag{14}$$

because P is a stochastic matrix and thus has eigenvalues equal to or less than one. The matrix BP has eigenvalues strictly less than one because $B < 1$. Consequently,

$$\lim_{N \to \infty} V(N) \equiv V = (I - BP)^{-1} Q \tag{15}$$

V is the vector of expected present values because each of its elements, V_i, is the present value of an infinite number of future expected social returns discounted by B.

Let $V^* = \max_d V^d$. A policy, d^*, is optimal if $V^{d^*} = V^*$. In terms of this formulation, the allocation problem for the resource manager is solved by finding the optimal policy assuming it exists. Ross (1969, pp. 119-24) has shown that in general it is sufficient for an optimal policy to exist if the number of states and policies are finite and q_i^d is bounded for all i and d. For this problem q_i^d is bounded, as is demonstrated in a later section, and therefore an optimal policy exists. Ross also shows that the optimal policy is stationary, meaning that it is nonrandom and that the action it chooses depends only on the state of the process.

Howard (1960) develops an iterative scheme for finding the optimal policy.[11] The algorithm consists of calculating the present value vector V in equation (15) for a given policy, d, and then determining a better policy if one exists by using a policy improvement routine. Once the improved policy is determined, its present value vector is calculated and then it too may be improved. Since there are only a finite number of policies, the improvement routine will eventually converge to the optimal policy. A complete description of the algorithm is presented in Appendix II.

Now let us consider the actual specification of the states, policies, social returns, and transition probabilities that comprise this model of the fishery.

C.2. Specification of States

The size of the stock (measured in some physical units depending on the resource) determines the state that the system occupies. There are S+1 possible states, X_i, for $i = 0, 1, 2, \ldots, S$. X_0 corresponds to the minimum stock of 0, and X_S represents the largest possible resource size, assumed to be the maximum sustainable population without predation by man in the case of a fishery, or the initial recoverable stock for a nonrenewable resource. The rest of the states occur at regular intervals between X_0 and X_S (see Figure II-1)

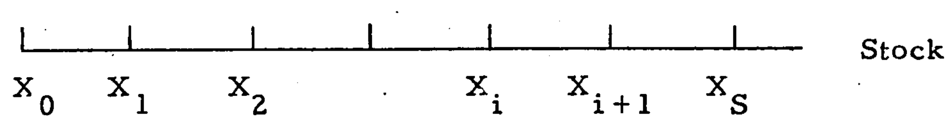

Figure II-1. Resource States

By increasing S we can represent the stock with greater precision. However, it becomes more expensive to solve the allocation problem as the number of states increase. Consequently, the choice of S involves a tradeoff between accuracy and computational costs.

C.3. Specification of Policies and Expected Social Returns

During each time period, the manager selects an effort allocation, E_i^m, from a finite number of possibilities. The "m" refers to the rate of effort and the "i" represents the state occupied by the resource. The possible allocations for each state i are represented by the array $(E_i^1, E_i^2, \ldots, E_i^m, \ldots, E_i^{M_i})$ where $E_i^m < E_i^{m+1}$. The maximum rate of effort for state i is $E_i^{M_i}$. It is equal to or less than the rate which maximizes the expected immediate returns from the resource.[12]

A policy is a rule for selecting an effort allocation in each state. To simplify the notation, assume policy d selects the "m th" effort rate in each state. Thus the allocations corresponding to policy d are represented by the array $(E_0^m, E_1^m, E_2^m, \ldots, E_S^m)$. The expected one period return from the resource in state i using policy d is

$$q_i^d = \mathcal{E}\, U(R(E_i^m, X_i) \tag{16}$$

where U is the social utility function and R is given by

$$R(E_i^m, X_i) = G(\eta_2\, g(X_i, E_i^m), \gamma_1) - C(E_i^m, \gamma_2) \tag{17}$$

The function G( ) is the total revenue plus consumer surplus generated by the resource extracted, $\eta_2 g(X_i, E_i^m)$, and C( ) is the total cost of effort. The random shift parameters, γ_1 and γ_2 appearing in G( ) and C( ) capture the effects of random changes in economic and social conditions on revenues and costs. For the case where costs and revenues are nonrandom but there is variation in the rate of extraction

$$q_i^d = \int_{z_1}^{z_2} U[G(\eta_2 g(X_i, E_i^m) - C(E_i^m)] \, h_2(\eta_2) \, d\eta_2 \tag{18}$$

where η_2 varies between z_1 and z_2. For situations where η_2 is a constant equal to one, but costs and revenues are random

$$q_i^d = \int_{x_1}^{x_2}\int_{w_1}^{w_2} U[G(g(X_i, E_i^m), \gamma_1) - C(E_i^m, \gamma_2)] \ell(\gamma_1, \gamma_2) \, d\gamma_1 \, d\gamma_2 \tag{19}$$

where $\ell(\gamma_1, \gamma_2)$ is the joint probability density function for γ_1 and γ_2 and γ_1 varies between x_2 and x_1 and γ_2 varies between w_2 and w_1. The array of expected social returns corresponding to policy d are represented by $(q_0^d, q_1^d, q_2^d, \ldots, q_S^d)$.

Recall that q_i^d must be bounded for the existence of an optimal policy in equation (15). This condition is satisfied by making the reasonable assumptions that G and C are bounded for finite E_i^m, and U is bounded for all finite R.

C.4. Specification of Transition Probabilities

This model is a "simple" or "one period" Markov process. The probability of making a transition to each state of the process depends on the state presently occupied and the policy d. The transitions occur at regular discrete time intervals. For convenience, define the time units so that the interval between transitions equals one. Then according to equation (4)

$$X_{t+1} = X_t + \eta_1 f(X_t) - \eta_2 g(X_t, E_t) \tag{20}$$

For convenience we have dropped the time subscript on η_1 and η_2. Suppose at time t, $X_t = X_i$, and policy d is being utilized. Then

$$X_{t+1} = X_i + \eta_1 f(X_i) - \eta_2 g(X_i, E_i^m) \tag{21}$$

By knowing the probability density functions for η_1 and η_2 is is possible to calculate the transition probabilities $p_{i,j}^d$ for all i and j, as we explain below.

a. Deterministic Case

The simplest case occurs when η_1 and η_2 are degenerate random variables with a mean equal to one. Then

$$X_{t+1} = X_i + f(X_i) - g(X_i, E_i^m) \tag{22}$$

If $X_{t+1} = X_j$ then $p_{i,j}^d = 1$ and $p_{i,n}^d = 0$ for all $n \neq j$. Suppose instead that X_{t+1} falls in between two states X_j and X_{j+1} such that $X_j < X_{t+1} < X_{j+1}$. Under these circumstances it is not clear how to calculate the transition probabilities. This problem arises because we are trying to represent a continuous variable by specifying only a finite number of values for that variable.

For instance when $X_j < X_{t+1} < X_{j+1}$ I have adopted the following convention. The probabilities $p^d_{i,j}$ and $p^d_{i,j+1}$ are calculated by the relative distance that X_{t+1} is from X_j and X_{j+1}. In particular

$$p^d_{i,j} = \frac{X_{j+1} - X_{t+1}}{X_{j+1} - X_j}$$

$$p^d_{i,j+1} = \frac{X_{t+1} - X_j}{X_{j+1} - X_j} \; ; \; p^d_{i,j} + p^d_{i,j+1} = 1 \tag{23}$$

The reason for choosing this method is as follows: Suppose that for two different effort rates E_i^m and E_i^{m+1}, the corresponding stock sizes in the following period shown in Figure II-2 and denoted by X^m_{t+1} and X^{m+1}_{t+1} both fall in the same interval between X_{j+1} and X_j. Since $E_i^m < E_i^{m+1}$ by equation (22) $X^m_{t+1} > X^{m+1}_{t+1}$

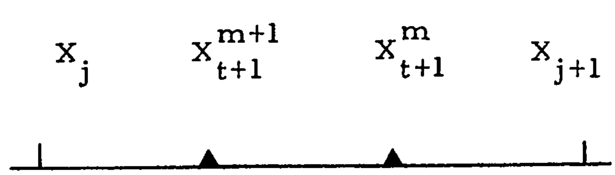

Figure II-2. Bounding Off Procedure

Using the method I have suggested, the fact that $X_{t+1}^{m} > X_{t+1}^{m+1}$ is indicated by the values of the transition probabilities. The probabilities act as weights to indicate the size of the stock relative to the states X_j and X_{j+1}. It is easy to verify that

$$X_{t+1}^{m} = p_{i,j}^{d} X_j + p_{i,j+1}^{d} X_{j+1}$$
$$X_{t+1}^{m+1} = p_{i,j}^{d+1} X_j + p_{i,j+1}^{d+1} X_{j+1} \tag{24}$$

where the transition probabilities are calculated according to equation (23). In this way it is easy to accurately monitor changes in the stock size corresponding to different policies.

Now let us consider some more complicated cases.

b. Random Growth Rate Case

Assume that only η_1 is random with probability density function $h_1(\eta_1)$ and η_2 is equal to one. From equation (21) the conditional probability density function for X_{t+1} given that $X_t = X_i$ for policy d, denoted by $H^d(X_{t+1}/X_i)$, can be derived for the following conditions[14]:

(a) If $f(X_i) \neq 0$ then

$$H^d(X_{t+1}/X_i) = h_1\left(\frac{X_{t+1} + g(X_i, E_i^m) - X_i}{f(X_i)}\right)\left|\frac{1}{f(X_i)}\right| \tag{25}$$

(b) If $f(X_i) = 0$ then the distribution for X_{t+1} is degenerate and the transition probabilities are calculated according to equation (23).

c. Random Depletion Rate Case

Assume that only η_2 is random with probability density function, $h_2(\eta_2)$ and η_1 is equal to one. By equation (20),

(a) If $g(X_i, E_i^m) \neq 0$ then

$$H^d(X_{t+1}/X_i) = h_2\left(\frac{f(X_i) + X_i - X_{t+1}}{g(X_i, E_i^m)}\right)\left|\frac{1}{g(X_i, E_i^m)}\right| \tag{26}$$

(b) If $g(X_i, E_i^m) = 0$ then the distribution for X_{t+1} is degenerate and the transition probabilities are calculated according to equation (23).

d. Random Depletion and Growth Rate Case ($\eta_1 = \eta_2$)

Assume that variations in the environment have the same effect on the growth rate and depletion rate of the stock. For this situation equation (20) becomes

$$X_{t+1} = X_t + \eta_1 [f(X_i) - g(X_i, E_i^m)] \tag{20}$$

and therefore,

(a) If $f(X_i) - g(X_i, E_i^m) \neq 0$ then,

$$H^d(X_{t+1}/X_i) = h_1\left(\frac{X_{t+1} - X_i}{f(X_i) - g(X_i, E_i^m)}\right)\left|\frac{1}{f(X_i) - g(X_i, E_i^m)}\right| \tag{27}$$

(b) If $f(X_i) - g(X_i, E_i^m) = 0$ then the distribution for X_{t+1} is degenerate and the transition probabilities are calculated according to equation (23).

e. Random Depletion and Growth Rate Case (η_1 and η_2 are independent)

Assume that η_1 and η_2 are completely independent of each other with probability functions $h_1(\eta_1)$ and $h_2(\eta_2)$.

(a) If $f(X_i) \neq 0$ then

$$H^d(X_{t+1}/X_i) = \int_{-\infty}^{\infty} h_i\left(\frac{\eta_2\, g(X_i, E_i^m) - X_i + X_{t+1}}{f(X_i)}\right)\left|\frac{1}{f(X_i)}\right| h_2(\eta_2)\, d\eta_2 \tag{28}$$

(b) If $f(X_i) = 0$ then $H^d(X_{t+1}/X_i)$ is calculated according to the variable depletion rate case in section C.4.c.

Suppose the condition probability density function $H^d(X_{t+1}/X_i)$ is represented in Figure II-3. In general the distribution of X_{t+1}

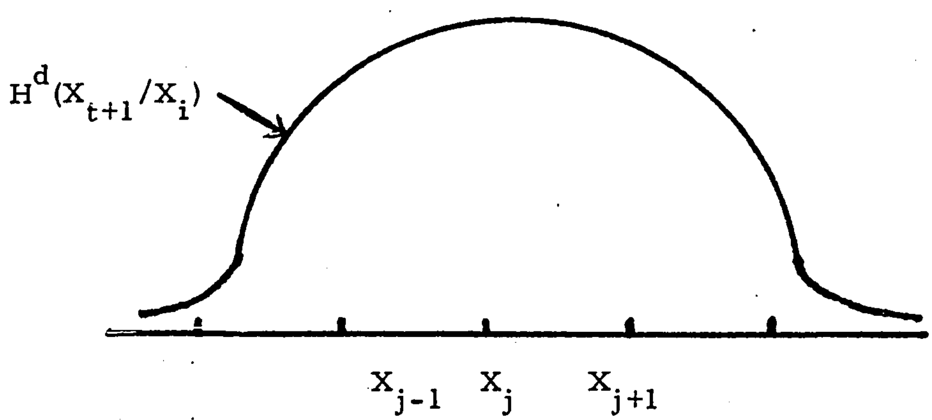

Figure II-3. Conditional Distribution of X_{t+1}

will be continuous since $h_1(\eta_1)$ and $h_2(\eta_2)$ are continuous. To transform $H^d(X_{t+1}/X_i)$ into a discrete density function, we define $\Phi_j(X)$ to be the function that assigns transition probabilities to state j such that

$$\text{if } X_j \le X \le X_{j+1} \qquad \text{and} \qquad \text{if } X_{j-1} \le X \le X_j$$

$$\text{then } p(X_j) = \frac{X_{j+1} - X}{X_{j+1} - X_j} \qquad \text{then } p(X_j) = \frac{X - X_{j-1}}{X_j - X_{j-1}} \tag{29}$$

where $p(X_j)$ is the probability that the fishery occupies X_j. Using $H^d(X_{t+1}/X_i)$ and $\Phi_j(X)$, the transition probability $p^d_{i,j}$ is calculated as

$$p^d_{i,j} = \int_{X_{j-1}}^{X_{j+1}} H^d(X_{t+1}/X_i)\, \Phi_j(X_{t+1})\, dX_{t+1} \tag{30}$$

$$\text{for } i,j = 0,1,2,\ldots,S .$$

In summary, the procedure for calculating the transition probabilities is:

1. If η_1 and η_2 are both constant, then the transition probabilities are calculated by equation (23).
2. If one or both of the variables, η_1 and η_2 are random then
   a. Derive the continuous probability density function given by $H^d(X_{t+1}/X_i)$.
   b. Use the function $\Phi_j(X)$ to transform $H^d(X_{t+1}/X_i)$ into a discrete density function with the probabilities given by equation (30).

D. EXTENSIONS OF THE MARKOV MODEL

The basic model presented in sections A-C will be used to study the Eastern Pacific yellowfin tuna fishery in Chapters III and IV. In specifying the model we have deliberately abstracted from certain complexities in order to isolate the effects of uncertainty about prices, and growth and depletion rates on optimal resource use. Nevertheless, our analysis is easily extended to accommodate other factors that presumably have an impact on resource allocation. Possible modifications in the model to account for the effects of seasonal variation, of systematic parameter changes over time, of interdependence between different resources, and of problems with observing the resource stock, on optimal management programs are presented below.

D. 1. Seasonal Variation[15]

The rate of growth for some resources, particularly the fishery, varies with the time of the year. Expected cost and revenues from the resource may also change with the season, as in the case of heating fuels. To account for these changes in our model each state could be characterized by the size of the stock as well as the season of the year. Then depending on the state, a particular growth equation for that season could be used to measure stock changes, and season specific cost and revenue functions could be employed to calculate profits.

D.2. Systematic Changes in Parameters over Time

Two limiting assumptions of our model are that (1) all of the parameter distributions are known with certainty, and (2) these distributions do not change over time. The first assumption is necessary because there is no feedback mechanism in our model for modifying parameter distribution estimates if these estimates are in error.[16] The second assumption, however, is unduly restrictive. Our model is easily modified to accommodate periodic, but predictable, changes in parameter distributions.

To account for these changes, each state could be characterized by the size of the stock as well as a description of the parameter distributions assumed. To illustrate, suppose that price is the only random variable in the model and it is uniformly distributed around a mean $\overline{p}$. Let us assume, that the mean price itself is variable, taking on values $\overline{p}_j$ for $j = 1, 2, 3, \ldots, J$ with $\overline{p}_j < \overline{p}_{j+1}$. Note that the entire distribution of prices shifts for a change in mean price. A typical state $S_{i,j}$ would be designated by a set of ordered pairs $(X_i, \overline{p}_j)$ for all i and j.

Suppose prices are expected to rise steadily over time due to a growing world demand for fish products. This effect could be incorporated in our analysis by specifying that the probability of moving from an initial state to one with a higher mean price is greater than moving to one with a lower price. The more rapid the expected rise in price is, the greater the probabilities would become in the direction of states with higher prices. In a similar fashion, by manipulating the transition probabilities, we could also capture the effects of decreasing and cyclical movements in prices.[17] Of course variations in other parameters besides price could be handled in the same way.

D.3. Interaction Between Different Resources[18]

In the marine ecosystem two or more populations may interact directly through the familiar predator-prey relationship, or more indirectly through the food chain. Besides this biological dependence, different species of fish may be economically related if they are good substitutes for each other in consumption. In the same fashion, the costs of extracting different minerals may be related since a variety of ores and metals may come from a single mine.

For simplicity suppose there are just two interrelated resources denoted by X and Z. Each stock may assume one of a finite number of sizes X_i for $i = 0, 1, 2, \ldots, I$, and Z_j for $j = 0, 1, 2, \ldots, J$. Each state in our model could be described by the current sizes of X and Z. Thus a typical state $S_{i,j}$ could be designated by a set of ordered pairs (X_i, Z_j) for all i and j.

Because of the mutual dependence between resources, a joint management program is advisable to achieve efficient resource use. Thus, in each time period optimal allocations of effort E^x and E^z for stocks X and Z respectively would be determined by the resource manager. For state $S_{i,j}$, the resulting payoff, $q_{i,j}$ would be

$$q_{i,j}(E^x, E^z) = \mathcal{E}\, U(R(X_i, Z_j, E^x, E^z)) \tag{31}$$

The right hand side of (31) is the expected utility of the rents from X and Z allowing for variation in revenues, costs, and/or depletion rates. Rents are equal to the joint revenue of the resources extracted from X and Z, minus the total cost of effort E^x and E^z.

In the case of fisheries, if X and Z are biologically interrelated then the one period changes in population size,

$$X_{t+1} - X_t = f(X_t, Z_t, E^z) \tag{32}$$

$$Z_{t+1} - Z_t = g(X_t, Z_t, E^z) \tag{33}$$

would depend on the current populations X_t and Z_t, and the amount of effort allocated for catching either X or Z. If, for example, Z was a predator of X then $\partial f/\partial Z_t < 0$ and $\partial g/\partial X_t > 0$. Assuming the functions f and g are known, calculation of the transition probabilities of moving from one state $S_{i,j}$ to another $S_{i',j'}$ would be straightforward.

D.4. Nonobservable Resource Stocks

Situations frequently occur where the size of the recoverable resource can't be observed directly. For example, one cannot directly observe the population of a fishery, although indications of the stock size can be obtained by noting the relative abundance of the population encountered while fishing. We shall consider situations for which a distribution of possible values for the resource stock can be derived in each period by a process described below, but that the exact size of the resource is not known.

Suppose initially, the distribution for X_0 is known, perhaps by some sampling routine. Although, the true stock, $\overline{X}_0$, is uncertain, we can calculate $\overline{X}_0$ for subsequent use in determining future stock sizes after observing resource production in period 0. Assuming the random variable η_2 is an observable quantity, such as water temperature or weather conditions in the case of fisheries, then for a given E_0, $\overline{X}_0$ is uniquely determined by observing the extraction rate $\eta_2\, g(\overline{X}_0, E_0)$.

The resulting stock in period 1 is

$$X_1 = \overline{X}_0 + \eta_1 f(\overline{X}_0) - \eta_2\, g(\overline{X}_0, E_0) \qquad (34)$$

Only if η_1 is observable can X_1 be calculated exactly. From this it follows that if the size of the resource is known in each period, as assumed in the basic model of sections A-C, we require that η_1 and η_2 be observed directly. If, however, η_1 is not observable, as we assume here, then one can only specify a distribution of possible values for X_1 from equation (34). In general, at any time t, we will only know the distribution of possible values for X_t from previous knowledge of X_{t-1}. Then, with separate observations on η_2, and $\eta_2\, g(\overline{X}_t, E_t)$, (for given E_t) we can determine the true stock $\overline{X}_t$. A distribution of values for X_{t+1} is then obtained by equation (35)

$$X_{t+1} = \overline{X}_t + \eta_1 f(\overline{X}_t) - \eta_2 g(\overline{X}_t, E_t) \tag{35}$$

and the process continues.

To incorporate this process in terms of a Markov model the states of the system would represent the distribution of possible stock sizes. Rewriting equation (35) we obtain

$$X_{t+1} = \mathcal{E}(X_{t+1}) + (\eta_1 - 1) f(\overline{X}_t) \tag{36}$$

where $\mathcal{E}(X_{t+1})$ is the expected value of the stock at time $t+1$. Thus, a typical state $S_{i,j}$ could be designated by a set of ordered pairs (X_i, V_j) where X_i is the expected value of the stock, $\mathcal{E}(X_{t+1})$ for $i = 0, 1, 2, \ldots, I$ and V_j is the distribution of the stock around its mean given by the second term on the right hand side of equation (36), for $j = 0, 1, 2, \ldots, J$. Since the distribution of η_1 is fixed, the distribution V_j is determined by $f(\overline{X}_t)$ which can assume one of a finite number of values. Assuming the distributions for η_1, and η_2 are known, calculation of the transition probabilities of moving from one state $S_{i,j}$ to another $S_{i',j'}$ would be straightforward.

For a given allocation of effort, E, the resulting payoff in state $S_{i,j}$ would be

$$q_{i,j}(E) = \int_{z_1}^{z_2} \mathcal{E}\, U(R(X_i + z, E)\, V_j(z)\, dz \tag{37}$$

where $\mathcal{E}U(R(X_i + z, E))$ is the expected utility of rents for a given stock size, $X_i + z$, assuming there is variation in revenues, costs, and/or extraction rates, and the distribution of stocks around X_i ranges between z_1 and z_2.

APPENDIX II

The Howard iteration scheme consists of calculating the present value vector, V, for a given policy; and then determining a better policy, if one exists by using a policy improvement routine. The entire method is shown schematically in the two boxes below.

Value Determination Operation

Use P^K and Q^K for a given policy K to solve for V^K

$$V^K = (I - BP^K)^{-1} Q^K$$

Policy Improvement Routine

Select the policy K' which maximizes

$$Q^{K'} + BP^{K'} V^K$$

using the present value vector, V^K, calculated in the Value Determination Operation. Once K' is determined it becomes the new policy in the Value Determination Operation

For each cycle, the policy improvement routine is able to make policy improvements until the policies on two successive iterations are the same. At this point the optimal policy or (policies, there may be more than one) has been determined and the problem is completed. The proof that the iteration cycle converges on the optimal policy is presented in Howard (1960, p. 84).

Footnotes

[1] See Howard (1960, p. 84).

[2] See Kuller and Cummings (1974).

[3] The assumption that resource depletion has no effect on extraction costs is usually introduced to simplify the analysis, but not because it is realistic. See Scott (1967, p. 27).

[4] The economic rent is defined to be the total revenue from the fish caught plus the producer's and consumer's surplus minus the total cost of fishing. Some care is needed in defining producer's surplus, see Mishan (1968).

[5] This is a partial equilibrium argument that assumes operations in the fishery do not significantly affect relative prices throughout the rest of the economy. Also, in principle it may be costly to redistribute income in which case it is not clear that maximizing the economic rent from the fishery is an optimal policy. For a discussion of this point see Bishop (1970).

[6] We are informed by Zoetewejj (1956) that share contracts between boat owners and fishermen predominate in marine fisheries.

[7] Contrary to this view that fishermen are risk averters, Gordon (1955, p. 132) states, "As those who know fishermen well have often testified, they are gamblers and incurably optimistic." This contention is hardly convincing however, as it is only supported by Gordon's personal observation.

[8] For a discussion of this question see Samuelson (1964) and Vickrey (1964), Hirshleifer (1966), Hirshleifer (1970), Baumol (1970) and Arrow and Lind (1970).

[9] In this case, the demand for the resource and the supply of E_t are both perfectly elastic and consumer's and producer's surplus are zero.

[10] See Luce and Raiffa (1957, p. 29).

[11] A linear programming approach, first suggested by Manne in "Linear Programming and Sequential Decisions," Management Science 6, No. 3, pp. 259-67 (1960), is also available for solving the Markov decision problem.

[12]It will never be optimal to allocate effort in excess of that which maximizes the immediate returns from the resource.

[13]We are assuming that policy d+1 selects the $m+1^{th}$ effort allocation.

[14]To derive equation (25) solve for η_1 as a function X_{t+1} from equation (21) with $\eta_1 = \psi(X_{t+1})$. The density function for X_{t+1} can then be written as $H(X_{t+1}) = h_1(\psi(X_{t+1}))\,|d\eta_1/dX_{t+1}|$; see Hoel (1962, pp. 381-83). Equations (26), (27), and (28) are derived analogously.

[15]To my knowledge the effects of seasonal variation on the fishery have not been analyzed in the fishery economics literature. Despite its title, the paper by Bradley (1970) entitled "Some Seasonal Models of the Fishing Industry" does not deal with seasonal variaion either.

[16]For a discussion of "feedback" or "adative expectation" models in economics see Nerlove (1972) and Rothschild (1972). An interesting analysis of adaptive decision making in the context of marine economics appears in Devanney (1971).

[17]By properly specifying the transition probabilities one can simulate a large variety of different parameter changes over time. For a discussion of the use of Markov models to simulate different processes over time see Feller (1950, Chapters XV and XVI) and Breiman (1969, Chapters 6 and 7).

[18]Some interesting examples of multiple species models appear in Quirk and Smith (1969) and Lampe (1967).

Chapter III

A DETERMINISTIC MODEL OF THE FISHERY

We are now ready to use the basic Markov decision process model introduced in sections A-C of Chapter II to study the Eastern Pacific yellowfin tuna fishery. Although our discussion will pertain to the fishery, the application of our model to the analysis of other resource problems should be apparent.

This chapter provides the framework for evaluating optimal programs of resource allocation in the yellowfin tuna fishery. In section A the economic and biological processes of the fishery are modelled in terms of a finite state and action Markov system. The model is intended to approximate conditions in the real world where, of course, a continuum of states and policies exist. Consequently, an accuracy check of the discrete Markov model is undertaken in sections B and C. First, in section B a control theory model which assumes a continuous "state variable," (population) and a continuous "control variable," (effort allocation) is employed to derive optimal allocation rules for the fishery under deterministic conditions. These rules are then compared with the optimal strategies obtained from the Markov decision model presented in section C, to determine the effects of discretizing the state and control variables. The Markov model performs quite well in that the solutions yielded by the programming and control theory methods are nearly identical. Finally, in section D the general form of the optimal deterministic policies are analyzed for their implications on current fishery management policy, and summarized for subsequent use in comparison with optimal stochastic decision rules appearing in Chapter IV.

A. A MARKOV MODEL OF THE EASTERN PACIFIC YELLOWFIN TUNA FISHERY

The Eastern Pacific yellowfin tuna provides an important source of income for fishermen from the United States, Canada, and several South and Central American countries. It is one of few international fisheries where the rate of fishing has been effectively controlled by a regulatory body, in this case the Inter-American Tropical Tuna Commission. Each year since 1966, the Commission has established a catch quota on yellowfin tuna to maintain the stock at a level producing the maximum sustainable physical yield.[1] For management purposes, the Tropical Tuna Commission, which is only one of three fishery commissions with an independent research staff, collects and analyzes data on the fishery so that the yellowfin tuna is one of the most extensively studied populations in the world. Consequently, besides the obvious reason that the tuna is a valuable resource, I decided to study this fishery because of the availability of reliable biological data.

In specifying a Markov model of the tuna fishery we begin by presenting the biological foundations of the fishery. A description

[1] See footnotes on pages 112-115.

of the economic conditions of the resource follows, and the model is completed by specifying the Markov states, policies, and transition probabilities.

A. 1. Biological Characteristics of the Fishery

The population dynamics of the Eastern Pacific yellowfin tuna are described by the Schaefer Stock Production model,[2] which is a special case of the general model of resource growth introduced in section A of Chapter II. According to the Schaefer model, the population at time $t+1$, denoted by X_{t+1} is[3]

$$X_{t+1} = X_t + \bar{\Delta} f(X_t) - \bar{\Delta} L_t \tag{1}$$

where $\bar{\Delta}$ is the length of each time interval. The population is expressed in terms of weight or biomass units. In the absence of predation by man the growth rate of the population is described by $f(X_t)$. Increases in the population include new "recruitment" to the fishable stock[4] and the "growth" of those fish already in the population. Natural decreases in the stock are caused by disease, predation by other fish, aging, and starvation.

Following Lotka (1956), $f(X)$ has the properties that $f(X^1) = f(X^2) = 0$, $f'(\hat{X}) = 0$, $f''(X) < 0$, and $0 \le X^1 < \hat{X} < X^2$.[4] Referring to Figure II-1, X^1 is the "critical population," populations below X^1 not being feasible because of inadequate reproduction and because of vulnerability to disease and predators.

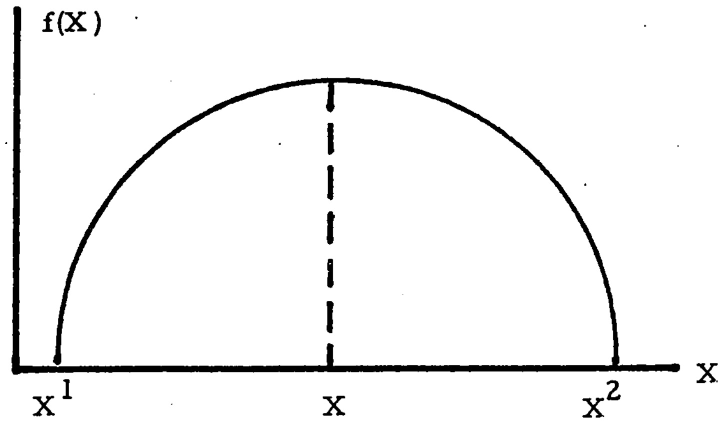

Figure III-1. Population Growth Curve

At X^2 the population is in natural equilibrium. The marginal increment to the population from recruitment and growth are exactly offset by the decrease caused by natural mortality. For the special case where $f(X)$ is a quadratic $(f(X) = (a - bX)X)$ the population increases according to the well known logistic law of growth.

When the population is exploited by a fishing industry, the rate of fish landings, L_t (measured in biomass units) is given by the function

$$L_t = g(X_t, E_t) \tag{2}$$

where fishing effort, E_t (measured in efficiency equivalent units) is a composite input variable representing the capital and labor used in fishing.

The Schaefer model assumes a particular functional form for

$f(X)$ and L. The complete model is:

$$f(X_t) = (a - bX_t)X_t ; \quad a, b > 0 \tag{3}$$

$$L_t = g(X_t, E_t) = kX_tE_t ; \quad k > 0 \tag{4}$$

$$X_{t+1} = X_t + \bar{\Delta}(a - bX_t)X_t - \bar{\Delta}kX_tE_t \tag{5}$$

Equation (4) describes a "mass contact" fishing technology where the catch rate is proportional to the physical contact between the fish and fishing effort. The constant, k, is called the "catchability coefficient" and is the per cent of the total fish population removed by one unit of effort.

The stochastic analogue to equation (5) suggested by Pella and Tomlinson (1969, p. 426) is

$$X_{t+1} = X_t + \bar{\Delta}\,[\eta_1(a - bX_t)X_t - \eta_2\, kX_tE_t] \tag{6}$$

The variable, η_1, represents random variation in the rate of production from the stock due to changes in recruitment, growth, and natural mortality caused by random changes in the environment. Variation in the landings rate due to random changes in availability and catchability is represented by the variable η_2. It is assumed that η_1 and η_2 are distributed independently over time with expected values $\mathcal{E}(\eta_1) = \mathcal{E}(\eta_2) = 1$. The distributions for η_1 and η_2 denoted by $h_1(\eta_1)$ and $h_2(\eta_2)$ are described in greater detail in section C.

Estimates for the population parameters, a, b, and k, presented in Table III-1, are based on historical time series data for catches and effort, and were provided by the Inter-American Tropical Tuna Commission. Details of the estimation procedure are described in Pella and Tomlinson (1969). According to Pella and Tomlinson, for these parameter values, a $\bar{\Delta}$ equal to 0.10 is sufficiently small such that the finite difference equation in (5) provides a good approximation for the instantaneous changes in population given by $\dot{X} = (a - bX)X - kXE$.

Table III-1. Population Parameter Estimates

Parameter	Estimated Value
a	3.057
b	1.035×10^{-8}
k	7.85×10^{-5}
$\bar{\Delta}$	0.10

A.2. Economic Characteristics of the Fishery

a. Specification of the Rent Function

The rent from fishing is

$$R(X_t, E_t) = \tilde{G}(L(X_t, E_t)) - C(E_t) \qquad (7)$$

where $\tilde{G}(L)$ is the total revenue and consumer surplus as a function of the catch, L, given by $L = kX_tE_t$, and $C(E_t)$ is the cost of fishing effort.

The price of tuna is determined on the world market, and the quantity of yellowfin taken from the Eastern Pacific is only a small fraction of the total world supply of tuna. Tuna products are also close substitutes for other fish products. Thus one would expect that the demand curve for yellowfin tuna from the Eastern Pacific is quite elastic. To test this hypothesis we regressed the price received for yellowfin tuna on the quantity purchased from the Eastern Pacific for the years 1958-1972; the data and estimation results appear in Appendix III-A. We found prices to be insensitive to the quantity of tuna purchased and consequently we shall assume

$$\tilde{G}(L) = pL \quad (8)$$

where $p = \$0.15$, is the mean price per pound for unprocessed yellowfin tuna during the 1966-1972 period, expressed in terms of 1956 dollars.

Several remarks need to be made concerning the estimation of the cost of effort function. Statistics on the costs of operation for tuna boats are generally not available. This is guarded information to most boat owners who are reluctant to reveal their financial situations.[6] Besides a lack of data, other factors complicate the estimation of $C(E_t)$. For example, most boats catch various fish besides yellowfin tuna, making it difficult to calculate the fraction of total cost attributed to fishing for yellowfin tuna. In addition, because of certain accounting procedures, reported costs often do not reflect the true opportunity costs of effort.[7] With these problems in mind, I have decided to assume three hypothetical specifications for $C(E_t)$ enabling us to study the effect of different cost conditions on optimal resource use.

The first of these specifications is

$$C(E_t) = 0 \tag{9}$$

The cost of effort is assumed to be zero. Although this is not representative of cost conditions in the yellowfin fishery, it is included here for general interest. If boats fishing for population A are simultaneously able to catch fish from another population B (without reducing the catch of A), then the opportunity cost of fishing for B is zero. As an example, boats that catch yellowfin spend most of their time trying to locate the yellowfin schools. During this time, other species of tuna such as the skipjack are often sighted and caught. Consequently, the opportunity cost of fishing for skipjack is virtually zero, assuming it does not interfere with the catch of yellowfin.[8]

The second specification is

$$C(E_t) = C_1E_t + C_2E_t^2; \quad C_1, C_2 > 0 \tag{10}$$

For this case $C(E_t)$ is convex, with costs increasing more than proportionately with the amount of effort. In the Schaefer model, E is strictly defined by the catch equation, $L = kXE$. It is an aggregate input with constant "fishing power," such that each unit removes a fraction k of the total population. To calculate $C(E_t)$ we must know the inputs comprising a unit of effort. An aggregate measure of these inputs is the number of days spent at sea, denoted by E^s, necessary to generate a given amount of total fishing effort, E. Expressing E^s as a function of E we have

$$E^s = h(E), \quad h' > 0 \tag{11}$$

The cost of E is defined by

$$C(E) = C^s(E^s) = C^s(h(E)), \quad C^{s\prime} > 0 \tag{12}$$

where C^s is the cost of E^s. The rate of increase in marginal cost given by

$$C''(E) = C^{s\prime\prime}(h(E))\, h'(E) + C^{s\prime}(h(E))\, h''(E) \tag{13}$$

is positive if the derivatives $h''(E)$ and $C^{s\prime\prime}(h(E))$ are both non negative with one strictly positive. If the minimum earnings needed to attract labor and capital at the margin rises as more of these inputs are employed in fishing then $C^{s\prime\prime} > 0$. The following arguments suggest we may also assume that $h''(E) > 0$.

Within given fishing grounds the amount of E^s needed to generate E depends on the travel time required to reach the area, prevailing weather conditions, ocean turbulence, the density of the stock in that area, etc. Fishermen naturally prefer areas that are close to port and that have favorable fishing conditions. As total effort increases these preferred areas become saturated with vessels and additional effort must be allocated in less desirable fishing grounds where more E^s is required to generate a certain amount of E. Also, the number of vessels operating in a given area may increase, reducing the efficiency of each boat because of crowding and congestion externalities.

The third functional form for $C(E_t)$

$$C(E_t) = C_3 E_t^{1/2} \tag{14}$$

has properties quite different from the previous specification. For this function $C(E_t)$ is concave, as average and marginal costs decrease with greater allocations of effort. From equation (13) $C''(E) < 0$ if the derivatives $C^{s''}$ and h'' are non positive with one strictly negative. If there are economies of scale in producing fishing gear or providing labor services then $C^{s''} < 0$. Assuming the number of vessels fishing in a given area increases as E increases, if there are gains in efficiency due to sharing information among boats about the location of the fish, then $h''(E) < 0$. In support of this possibility, Orbach (1975) reports that the practice of different boats sharing information with each other is quite common in the Eastern Pacific fleet.

Naturally, for the reasons we mentioned before, the information necessary to estimate the values of C_1, C_2, and C_3 is not available. Therefore, we assume a range of different values for these parameters to determine the optimal response in resource allocation to different levels of cost.

In all of these specifications the fixed costs of effort are zero. The large purse seiners[9] that dominate fishing in the Eastern Pacific are quite mobile and can operate in numerous fisheries throughout the world. Because of the availability of other species in the same area, such as the skipjack, and the easy access to other fishing grounds, the fixed costs of fishing for yellowfin in the Eastern Pacific are minimal.

b. Specification of Utility Functions

With the equation for fishery rents in (7) formulated in terms of the revenue and cost functions presented above, we have only to specify some suitable forms for the social welfare function to complete the economic component of our model. To accommodate different social attitudes for risk bearing in our analysis, an important consideration in Chapter IV, two specifications of the welfare function are assumed.

$$U(R) = R \tag{15}$$

and

$$U(R) = \ln(R + G); \quad G = 4.5 \times 10^8 \tag{16}$$

Due to the curvature of these functions, (15) reflects a risk neutral attitude and (16) exhibits a risk averse attitude toward variability in the returns from the fishery. The natural log function in (16) was chosen because it is easy to work with computationally. In stochastic models, where variations in rents occur, it is possible for R to be negative. To insure that $\ln(R+G)$ exists, the constant G is specified to be large enough such that $R + G > 0$ for all possible values of R. The procedure for determining G is discussed in Appendix III-B.

Of course these welfare functions are only hypothetical. The problem of actually estimating and providing a consistent representation of social risk preferences is a very difficult one, and we shall not attempt to resolve it here. I shall defer a discussion of this problem until the stochastic model is introduced in Chapter IV.

The two utility specifications combined with the various forms of the rent function we have presented yield the six classes of objective functions appearing in Table III-2. The analysis that follows is carried through for each of these six classes. Each function is characterized by cost conditions in the fishery as well as the social attitudes toward risk bearing that exist.

Table III-2. Classes of Objective Functions

Function	Class
pkX_tE_t	I
$pkX_tE_t - C_1E_t - C_2E_t^2$	II
$pkX_tE_t - C_3E_t^{1/2}$	III
$\ln(pkX_tE_t + G)$	IV
$\ln(pkX_tE_t - C_1E_t - C_2E_t^2 + G)$	V
$\ln(pkX_tE_t - C_3E_t^{1/2} + G)$	VI

A. 3. Specification of States, Allocation Policies, and Transition Probabilities

The description of the biological and economic characteristics of the Eastern Pacific yellowfin fishery is complete, and we are ready to form the structure for the discrete Markov model.

a. Specification of States

There are 31 possible states for the fishery, denoted by X_i, for $i = 0, 1, 2, \ldots, 30$. Each state corresponds to a certain population size given by $X_i = i \times 10^7$ pounds. X_0 represents the minimum stock of 0 pounds, and X_{30} is the largest population. The parameter estimates in Table III-1 indicate a maximum sustainable stock of 29.4×10^7 pounds so that $X_{30} = 30 \times 10^7$ pounds is large enough to include all probable values of the population. Since the Tropical Tuna

Commission generally tries[10] to maintain the stock at a level producing the maximum sustained yield, the current population is probably in the neighborhood of 15×10^7 pounds.[11]

b. Specification of Allocation Policies

There are a finite number of possible effort allocation corresponding to each state of the system. These allotments of effort are measured in terms of boat days at sea, and range in multiples of 250 from a minimum of 0 days to a maximum amount determined by economic conditions. Obviously, an upper bound on effort in each state, i, is the level that maximizes $R(X_i, E)$, since it is never optimal to allocate effort beyond that point.

c. Specification of Transition Probabilities

The probability of the system moving from one state to another is a function of the state currently occupied, and the allocation policy of the resource manager. For deterministic systems the calculation of transition probabilities is according to equation (23) in section C.4.a of Chapter II. For stochastic models, depending on the type of stochastic variation, the transition probabilities are specified according to equations (25) - (30) in sections C.4.b. - C.4.d. of Chapter II.

B. CONTROL THEORY SOLUTION TO THE ALLOCATION PROBLEM

With a descriptive model of the yellowfin tuna industry we proceed to a consideration of optimal resource use in the fishery, over time, under deterministic conditions. In formal terms, the allocation problem is to

$$\underset{E_t}{\text{maximize}} \sum_{t=0}^{\infty} B^t [U(R(X_t, E_t))] \bar{\Delta} \tag{17}$$

subject to

$$X_{t+1} = X_t + [(a - bX_t)X_t - kX_tE_t] \bar{\Delta} \tag{18}$$

$$X_t \geq 0 \tag{19}$$

$$X_0 = \hat{X} \tag{20}$$

$$0 \leq E_t \leq E_{max} \tag{21}$$

where $U(R(X_t, E_t))$ belongs to one of the six classes of objective functions listed in Table III-2, and B is the social discount factor equal to the reciprocal of one plus the social discount rate. Equations (19) and (20) represent the non-negativity and initial conditions for the stock, and (21) restricts effort allotments to be non-negative and less than or equal to some maximum amount denoted by E_{max}.[12]

As mentioned before, the problem is amenable to solution by dynamic programming methods or optimal control theory. For each class except III and VI, solutions to the allocation problem are derived using both procedures. Then in section C, they are compared to evaluate the accuracy of the finite state and action Markov decision process. Certain concavity conditions on the objective function sufficient for the control theory solution to be optimal are not satisfied for Classes III and VI, so that these cases can only be solved with the Markov decision model.

Proceeding with the control theory analysis, we first describe the optimal time paths of effort and catches in general terms for Classes I, II, IV, and V. Then, a method to compute these paths for specific cases is introduced. The results of these computations are presented in section C for comparison with the Markov model solutions.

B. 1. Control Theory Formulation

The allocation problem posed above is well defined. One seeks to maximize the discounted stream of social returns from the fishery by choosing the correct value for the control, E_t, subject to adjustments in the population described by equation (18). The convergence of the welfare functional is assured if the initial population size is finite, and $B < 1$. If X_0 is less than or equal to the maximum sustainable population, a/b, then

$$\sum_{t=0}^{\infty} B^t[U(R(X_t, E_t))]\overline{\Delta} \leq \sum_{t=0}^{\infty} B^t[U(R(a/b, E_t))]\overline{\Delta}$$

$$< \frac{U^*(R(a/b, E))}{1 - B} \qquad (22)$$

where E_t is contained in the set of admissible controls defined by (21), and $U^* = \max_{E_t} U(R(X_t, E_t))$. If X_0 is greater than a/b but finite then,

$$\sum_{t=0}^{\infty} B^t[U(R(X_t, E_t))]\overline{\Delta} \leq \sum_{t=0}^{\infty} B^t[U(R(X_0, E_t))]\overline{\Delta}$$

$$< \frac{U^*(R(X_0, E))\overline{\Delta}}{1 - B}$$

Applying Pontryagin's Maximum Principle, the necessary conditions for maximization of (17) subject to (18) - (21) are that there exists a costate variable, λ_{t+1}, such that the control, E_t, maximizes, H, the Hamiltonian at each instant in time where,[13]

$$H = B^t[U(R(X_t, E_t)) + B\lambda_{t+1}((a - bX_t)X_t - kX_tE_t)] \qquad (24)$$

with

$$\frac{\partial H}{\partial E_t} = B^t \left| U' \frac{\partial R}{\partial E_t} - B\lambda_{t+1} kX_t \right| \overline{\Delta} \begin{matrix} \leq \\ = \\ \geq \end{matrix} 0 \text{ if } \begin{cases} E_t = 0 \\ 0 < E_t < E_{max} \\ E_t = E_{max} \end{cases} \qquad (25)$$

$$X_{t+1} - X_t = [(a - bX_t)X_t - kX_tE_t]\,\overline{\Delta} \tag{26}$$

$$\lambda_{t+1} - \lambda_t = -\; U'\frac{\partial R}{\partial X_t} + B\lambda_{t+1}\left(a - 2bX_t - kE_t - \frac{1-B}{\overline{\Delta} B}\right)\overline{\Delta} \tag{27}$$

Sufficient conditions for an optimum are the transversality condition

$$\lim_{T \to \infty} B^{T+1}\,\lambda_{T+1}\,X_T = 0 \tag{28}$$

and that the maximized Hamiltonian be concave with respect to the state variable X. The concavity requirement is trivially satisfied for Classes I and IV. That the condition also holds for Classes II and V is readily verified once the optimal time paths for effort and catches are computed.

B.2. Economic Interpretation

If at some time, t, we have an interior solution with ($X_t > 0$, $\lambda_{t+1} > 0$, $0 < E_t < E_{max}$) then equation (25) implies

$$U'\frac{\partial R}{\partial E_t} - B\lambda_{t+1}\,kX_t = 0 \;, \tag{25$'$}$$

where λ_{t+1} is the marginal value of the fishery stock at time $t+1$. This condition implies that along the optimal time path of the control variable, E_t, the marginal addition to current utility, $U'\frac{\partial R}{\partial E_t}$, from increasing the catch is exactly offset by the resulting marginal decrease in population available next period with the stock valued at its marginal worth discounted for time, $B\lambda_{t+1}$. Equation (26) specifies the net growth in the stock as a function of natural growth and the reduction in the population attributed to fishing. Rewriting equation (27) yields

$$\frac{-(B\lambda_{t+1} - \lambda_t)}{\bar{\Delta}} = U' \frac{\partial R}{\partial X} + B\lambda_{t+1}(a - 2bX_t - kE_t) \qquad (27)'$$

The left hand side of (27)′ is the rate at which the value of the stock depreciates in present value terms. It equals the rate an additional unit of the stock adds to current utility, $U' \frac{\partial R}{\partial X}$, plus the rate it enhances the value of the existing stock.

B.3. Description of the Optimal Time Paths

a. Classes II, IV, and V

Assuming an interior solution for (25) it is possible under certain conditions to represent[14] E_t as a function of X_t and λ_{t+1}. The Jacobian of (25)′

$$J = U''\left(\frac{\partial R}{\partial E}\right)^2 + U' \frac{\partial^2 R}{\partial E^2} < 0 \qquad (29)$$

is non vanishing for Classes II, IV, and V since either U or R are strictly concave. Substituting for E_t in terms of X_t and λ_{t+1} from (25)′, we generate a system of two autonomous first order difference equations for ΔX_t and $\Delta \lambda_t$.[15] A stationary equilibrium

(X^*, λ^*) for this system exists for[16]

$$\Delta X_t = (a - bX_t)X_t - kX_t E_t(X_t, \lambda_{t+1}) = 0 \tag{30}$$

and

$$\Delta\lambda_t = -\Big[U' \frac{\partial R}{\partial X_t}(X_t, E_t(X_t, \lambda_{t+1})) + B\lambda_{t+1}\Big(a - 2bX_t - \frac{1-B}{\bar{\Delta}B} - kE_t(X_t, \lambda_{t+1})\Big)\Big] = 0 \tag{31}$$

Equation (30) implies equilibrium between the natural growth rate of the stock and the harvest rate by the fishermen. Rewriting equation (31) yields

$$U' \frac{\partial R}{\partial X_t} + B\lambda_{t+1}(a - 2bX_t - kE_t) = \frac{(1-B)}{\bar{\Delta}}\lambda_{t+1} \tag{31$'$}$$

The term $\frac{(1-B)}{\bar{\Delta}}\lambda_{t+1}$ is the rate at which the value of the stock is discounted. The total value discounted in one period is $(1-B)\lambda_{t+1}$ and thus $\frac{(1-B)}{\bar{\Delta}}\lambda_{t+1}$ is the rate of discount. Equation (31)′ implies that the interest on the stock, $\frac{(1-B)}{\bar{\Delta}}\lambda_{t+1}$, equals the rate which an addition to the population increases current utility, $U'\frac{\partial R}{\partial X_t}$, plus the rate which it enhances the current discounted value of the stock available next period, $\lambda_{t+1}B(a - 2bX_t - kE_t)$.

We now prove that if a stationary point exists, then

$$\frac{a - \dfrac{1-B}{\bar{\Delta} B}}{2b} < X^* < \frac{a}{b}$$

As we shall see $\dfrac{a - \dfrac{1-B}{\bar{\Delta}B}}{2b}$ is the stationary equilibrium for the costless effort case, Class I, and $\dfrac{a}{b}$ is the equilibrium occurring when the fishery is left unexploited. Rewriting (31) we obtain

$$U' \frac{\partial R}{\partial X_t} - B\lambda_{t+1} kE_t = -B\lambda_{t+1}\left(a - 2bX_t - \frac{(1-B)}{\bar{\Delta}B}\right) \qquad (32)$$

From (25)′

$$B\lambda_{t+1} k = \frac{U' \dfrac{\partial R}{\partial E_t}}{X_t} \quad .$$

Substituting for $B\lambda_{t+1}$ above yields

$$U'\left[\frac{\partial R}{\partial X_t} - \frac{\partial R}{\partial E_t}\frac{E_t}{X_t}\right] = -B\lambda_{t+1}\left(a - 2bX_t - \frac{(1-B)}{\bar{\Delta}B}\right) \qquad (33)$$

Recalling that $R(X_t, E_t) = pkX_tE_t - C(E_t)$, the left hand side of (33) becomes $U'C'(E_t)\dfrac{E_t}{X_t}$ which is strictly positive for $E_t > 0$. This implies

$$a - 2bX_t - \frac{(1-B)}{\bar{\Delta}B} < 0 \quad \text{or} \quad X_t > \frac{a - \dfrac{1-B}{\bar{\Delta}B}}{2b} \quad \text{since} \quad \lambda_{t+1} > 0 \ .$$

If $\left(a - \dfrac{1-B}{\bar{\Delta}B}\right) < 0$, a stationary equilibrium for this case does not exist; however $\left(a - \frac{1-B}{\bar{\Delta}B}\right) > 0$ for the examples in this chapter.

From (30) with $E_t > 0$, $\Delta X_t = 0$ only for $X_t < \frac{a}{b}$. Therefore we have

$$\frac{a - \frac{1-B}{\bar{\Delta}B}}{2b} < X^* < \frac{a}{b}$$

This result is significant in that it implies that X^*, the steady state population, may equal $a/2b$, the maximum sustainable yield population. However, as we will see, there is no a priori reason to suspect that the two populations will coincide.

The intersection of the $\Delta X = 0$ and the $\Delta\lambda = 0$ curves and the resulting stationary point (X^*, λ^*) are illustrated in Figure III-2. To see that at least one stationary point exists in the interval,

$\left(\frac{a - \frac{1-B}{\bar{\Delta}B}}{2b}, \frac{a}{b}\right)$, consider the values of λ_{t+1} evaluated at

$X_t = \frac{a - \frac{1-B}{\bar{\Delta}B}}{2b}$ and $X_t = \frac{a}{b}$ along the $\Delta X = 0$ and $\Delta\lambda = 0$ curves.

From equations (30) and (31) it is readily verified that

$$E_t\Big|_{\Delta X = 0} > E_t\Big|_{\Delta\lambda = 0} \quad \text{for} \quad X_t = \frac{a - \frac{1-B}{\bar{\Delta}B}}{2b}$$

$$E_t\Big|_{\Delta X = 0} < E_t\Big|_{\Delta\lambda = 0} \quad \text{for} \quad X_t = \frac{a}{b} \tag{34}$$

By equation (25)′

$$\frac{\partial E_t}{\partial \lambda_{t+1}} = \frac{BkX_t}{J} < 0 \tag{35}$$

implying that

$$\lambda_{t+1}\Big|_{\Delta X = 0} < \lambda_{t+1}\Big|_{\Delta\lambda = 0} \quad \text{for } X_t = \frac{a - \frac{1-B}{\bar{\Delta}B}}{2b}$$

$$\lambda_{t+1}\Big|_{\Delta X = 0} > \lambda_{t+1}\Big|_{\Delta\lambda = 0} \quad \text{for } X_t = \frac{a}{b}. \tag{36}$$

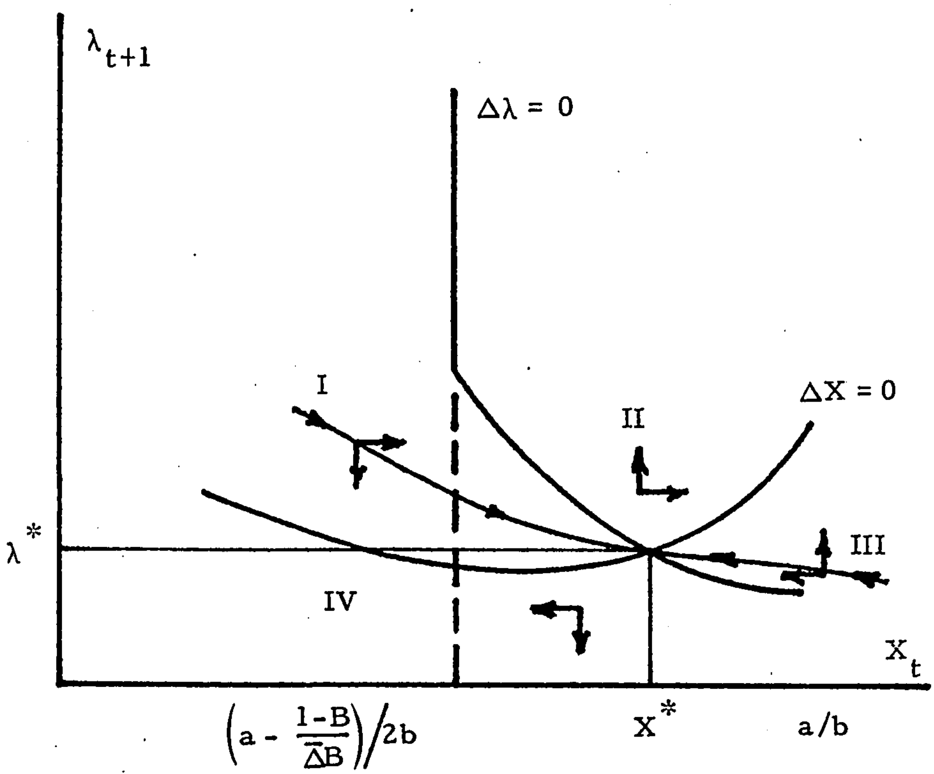

Figure III-2. Phase Diagram

Since the $\Delta\lambda = 0$ and $\Delta X = 0$ curves are continuous, they must intersect at one or more points in the $\lambda_{t+1} - X_t$ plane for X_t in the interval $\left(\frac{a - \frac{1-B}{\bar{\Delta}B}}{2b}, \frac{a}{b} \right)$, thus proving the existence of a stationary equilibrium. Furthermore, the equilibrium is unique, for the examples considered here, as we shall see once the optimal time paths are computed.

Consider the direction of motion of a point (X_t, λ_{t+1}) lying above or below each of the $\Delta\lambda = 0$ and the $\Delta X = 0$ curves. For points above the $\Delta X = 0$ curve, $\Delta X > 0$, and for points below the curve $\Delta X < 0$ since

$$\left. \frac{d\Delta X}{d\lambda_{t+1}} \right|_{X_t = \text{constant}} = -kX_t \frac{\partial E_t}{\partial \lambda_{t+1}} > 0 \qquad (37)$$

If $X_t < \frac{a - \frac{1-B}{\bar{\Delta}B}}{2b}$ then $\Delta\lambda < 0$. Otherwise, for $X_t \geq \frac{a - \frac{1-B}{\bar{\Delta}B}}{2b}$

$$\left. \frac{d\Delta\lambda}{d\lambda_{t+1}} \right|_{X_t = \text{constant}} = -\left[\frac{\partial E_t}{\partial \lambda_{t+1}} \left[U'' \frac{\partial R}{\partial X_t} \frac{\partial R}{\partial E_t} + U' \frac{\partial^2 R}{\partial E_t \partial X_t} - B\lambda_{t+1} k \right] + B \left[a - \frac{1-B}{\bar{\Delta}B} - 2bX_t - kE_t \right] \right] \qquad (38)$$

From $(25)'$ we obtain

$$\frac{\partial E_t}{\partial \lambda_{t+1}} \left[U'' \frac{\partial R}{\partial E_t} \frac{\partial R}{\partial X_t} + U' \frac{\partial^2 R}{\partial E_t \partial X_t} - B\lambda_{t+1} k \right] = -BkX_t \frac{\partial E_t}{\partial X_t} \quad (39)$$

and thus

$$\left.\frac{d\Delta\lambda}{d\lambda_{t+1}}\right|_{X_t = \text{constant}} = B\left(kE_t + kX_t \frac{\partial E_t}{\partial X_t}\right) - B\left(a - \frac{1-B}{\bar{\Delta}B} - 2bX_t\right) \quad (40)$$

The second term on the right hand side of (40) is non negative since

$X_t \geq \dfrac{a - \frac{1-B}{\bar{\Delta}B}}{2b}$. Consequently $\left.\dfrac{d\Delta\lambda}{d\lambda_{t+1}}\right|_{X_t = \text{constant}} > 0$ for $\dfrac{\partial E_t}{\partial X_t} \geq 0$

Suppose that $\dfrac{\partial E_t}{\partial X_t} < 0$, then from (25)′

$$\left|\frac{\partial E_t}{\partial X_t}\right| = \left| - \frac{U'' \frac{\partial R}{\partial E_t} \frac{\partial R}{\partial X_t} + U' \frac{\partial^2 R}{\partial E_t \partial X_t} - B\lambda_{t+1} k}{U''\left(\frac{\partial R}{\partial E_t}\right)^2 + U' \frac{\partial^2 R}{\partial E_t^2}} \right| \quad (41)$$

$$< \frac{U'' \frac{\partial R}{\partial E_t} \frac{\partial R}{\partial X_t}}{U''\left(\frac{\partial R}{\partial E_t}\right)^2} = \frac{\frac{\partial R}{\partial X_t}}{\frac{\partial R}{\partial E_t}}$$

since $\left[U'' \dfrac{\partial R}{\partial E_t} \dfrac{\partial R}{\partial X_t} + U' \dfrac{\partial^2 R}{E_t \partial X_t} - B\lambda_{t+1} k \right] < 0$ by virtue of assuming

$\dfrac{\partial E_t}{\partial X_t} < 0$, and $\left[U' \dfrac{\partial^2 R}{\partial E_t \partial X_t} - B\lambda_{t+1} k \right] = U' \dfrac{C'(E_t)}{X_t} > 0$. Therefore, for points on the $\Delta\lambda = 0$ curve

$$\left.\frac{d\Delta\lambda}{d\lambda_{t+1}}\right|_{\substack{X_t = \text{constant} \\ \Delta\lambda = 0}} > \left[BkE_t - BkX_t \left(\frac{\frac{\partial R}{\partial X_t}}{\frac{\partial R}{\partial E_t}} \right) - B \left(a - \frac{1-B}{\bar{\Delta} B} - 2bX_t \right) \right]$$

$$= \left[BkE_t - U' \frac{\frac{\partial R}{\partial X_t}}{\lambda_{t+1}} - B \left(a - \frac{1-B}{\bar{\Delta} B} - 2bX_t \right) \right] = \frac{\Delta\lambda}{\lambda} = 0 \quad (42)$$

Consequently for points lying to the left and below the $\Delta\lambda = 0$ curve $\Delta\lambda < 0$, and for points lying above and to the right of the curve then $\Delta\lambda > 0$.

The arrows in Figure III-2 indicate the direction of movements of points in the phase space. If X_0 is greater than (less than), X^* there exists a λ_1 in region I, (III) such that the path beginning at $(X_0 \lambda_1)$ converges to $(X^* \lambda^*)$. This is the optimal path as it satisfies the necessary conditions (25) - (27), and the transversality condition (28). All other paths either begin in or eventually enter region II or IV from where it is impossible to reach the stationary equilibrium.

To show that $(X^* \lambda^*)$ is a saddle point expand, ΔX and $\Delta\lambda$ about $(X^* \lambda^*)$ as a Taylor series, including only linear terms.

$$\begin{bmatrix} \Delta X \\ \Delta\lambda \end{bmatrix} = A \begin{bmatrix} X^* - X \\ \lambda^* - \lambda \end{bmatrix} .$$

where

$$A = \begin{bmatrix} \frac{\partial \Delta X}{\partial X} & \frac{\partial \Delta X}{\partial \lambda} \\ \frac{\partial \Delta \lambda}{\partial X} & \frac{\partial \Delta \lambda}{\partial \lambda} \end{bmatrix}$$

with all the elements of A evaluated at $(X^* \lambda^*)$. Since

$$\frac{\partial \Delta X}{\partial X} = - \frac{d\lambda}{dX}\Bigg|_{\Delta X = 0} \frac{\partial \Delta X}{\partial \lambda}$$

and

$$\frac{\partial \Delta \lambda}{\partial X} = - \frac{d\lambda}{dX}\Bigg|_{\Delta \lambda = 0} \frac{\partial \Delta \lambda}{\partial \lambda}$$

$$A = \begin{bmatrix} - \frac{d\lambda}{dX}\Big|_{\Delta X = 0} & \frac{\partial \Delta X}{\partial \lambda} & \frac{\partial \Delta X}{\partial \lambda} \\ - \frac{d\lambda}{dX}\Big|_{\Delta \lambda = 0} & \frac{\partial \Delta \lambda}{\partial \lambda} & \frac{\partial \Delta \lambda}{\partial \lambda} \end{bmatrix} .$$

The eigenvalues for A, ξ_1 and ξ_2 are determined by the equation,

$$\xi^2 + \xi \left[\frac{d\lambda}{dX}\Bigg|_{\Delta X = 0} \frac{\partial \Delta X}{\partial \lambda} - \frac{\partial \Delta \lambda}{\partial \lambda} \right] + \left[\frac{d\lambda}{dX}\Bigg|_{\Delta \lambda = 0} - \frac{d\lambda}{dX}\Bigg|_{\Delta X = 0} \right] \frac{\partial \Delta X}{\partial \lambda} \frac{\partial \Delta \lambda}{\partial \lambda} = 0 \tag{43}$$

Looking at the constant term, $\left[\frac{d\lambda}{dX}\Big|_{\Delta \lambda = 0} - \frac{d\lambda}{dX}\Big|_{\Delta X = 0} \right] < 0$ since the $\Delta\lambda = 0$ curve intersects the $\Delta X = 0$ curve from above. The entire term is negative since $\frac{\partial \Delta X}{\partial \lambda}$ and $\frac{\partial \Delta \lambda}{\partial \lambda}$ are positive. This implies that the eigenvalues are real and of opposite sign so that $(X^* \lambda^*)$ is a saddle point.

b. Class 1

Spence (1973) has identified certain classes of control problems that have solutions of the following type. First, one determines an optimal stationary level for the state variable (for our problem it is the population). Then, regardless of the initial population, one proceeds as rapidly as possible to the stationary state and remains there forever. Time paths of this sort are referred to as most rapid approach paths. Formally, in terms of our model, a path $\tilde{X}_t$ is called a most rapid approach path with respect to X_0 and X^* if $\tilde{X}_0 = X_0$, and the appropriate condition below is satisfied:

$$\begin{aligned} &\text{(a)} \quad \text{for } \tilde{X}_t < X^*: \ \tilde{X}_{t+1} = \min\{X^*, \tilde{X}_t + (a - b\tilde{X}_t)\tilde{X}_t \bar{\Delta}\} \\ &\text{(b)} \quad \text{for } \tilde{X}_t > X^*: \ \tilde{X}_{t+1} = \max\{X^*, \tilde{X}_t + [(a - b\tilde{X}_t)\tilde{X}_t - k\tilde{X}_t E_{max}]\bar{\Delta}\} \\ &\text{(c)} \quad \text{for } \tilde{X}_t = X^*: \ \tilde{X}_{t+1} = X^* \end{aligned} \tag{44}$$

There may be an intermediate period in which E_t equals neither of its extreme values, nor the level which well sustain the state variable at X^*. It is the period in which the transition from rapid ascent or descent is made to X^*.

Spence demonstrates for discrete control problems that a sufficient condition for most rapid approach paths to be optimal is that the objective function be implicitly additively separable in X_t and X_{t+1}. In terms of our model the appropriate condition is that $R(X_t, E_t)$ may be written in terms of equation (45),

$$R = a(X_t) + b(X_{t+1}) ; \qquad (45)$$

where a(*) and b(*) are functions. This condition is satisfied for control problems having a Class I specification of rents. First, we write E_t in terms of X_t and X_{t+1} from equation (26)

$$E_t = \frac{X_t + \bar{\Delta}(a - bX_t)X_t - X_{t+1}}{\bar{\Delta} k X_t} \qquad (46)$$

Substituting for E_t in the rent function we obtain,

$$R(X_t, X_{t+1}) = \frac{p(X_t + \bar{\Delta}(a - bX_t)X_t)}{\bar{\Delta}} - \frac{pX_{t+1}}{\bar{\Delta}} \qquad (47)$$

Equation (47) is additively separable in X_t and X_{t+1} indicating that most rapid approach paths are optimal for Class I problems. From equations (30) and (31) it is easy to verify that the optimal stationary state occurs for $X^* = \dfrac{a - \dfrac{1 - B}{\bar{\Delta} B}}{2b}$.

B.4. Computation of Optimal Paths

To calculate the optimal paths for Class I problems first one determines the value for the optimal stationary state X^*. Then depending on the initial population, one selects the level of effort according to the conditions in equation (44) in order to reach X^* as quickly as possible.

For Classes II, IV, and V the calculation of optimal paths begins by determining the values for the steady state population X^*, and the costate variable λ^*, from equations (30) and (31). For all the examples considered in this chapter, the stationary point $(X^* \lambda^*)$ is unique. Then for a given initial population X_0, one chooses an initial value for the costate variable λ_1, as depicted in the phase diagram of Figure III-3. The resulting path consisting of a series of discrete points is simulated on the computer according to equations (25) - (27). If the path converges to $(X^* \lambda^*)$ it is the optimal one, otherwise if the path enters region IV (II) the simulation is repeated

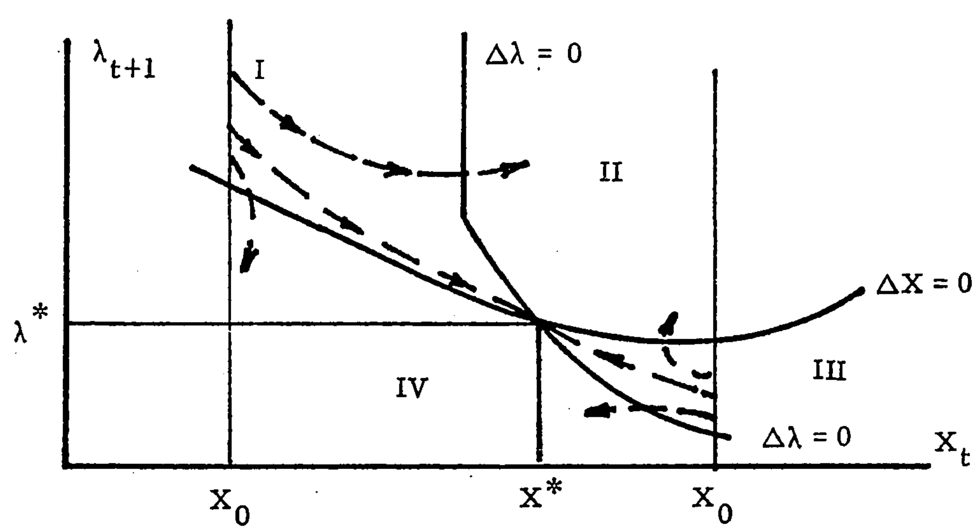

Figure III-3. Selection of Optimal Paths with a larger (smaller) value for λ_1 -- see Figure III-3. This process is continued until a "resonably convergent" path is located -- one which comes within a very close range of reaching $(X^* \lambda^*)$ without leaving regions I or III.[18]

The optimal path corresponding to a given X_0 consists of discrete jumps in the state and costate variable, and thus contains only a certain number of points in the phase plane. Therefore, optimal paths originating from various initial populations are determined in order to generate a locus of optimal points in the fashion illustrated in Figure III-4.

Clearly, the optimal effort allocation at time t depends only on X_t. According to equation (25), E_t is a function of X_t and λ_{t+1}; however, λ_{t+1} is also a function of X_t. The graph of λ_{t+1}

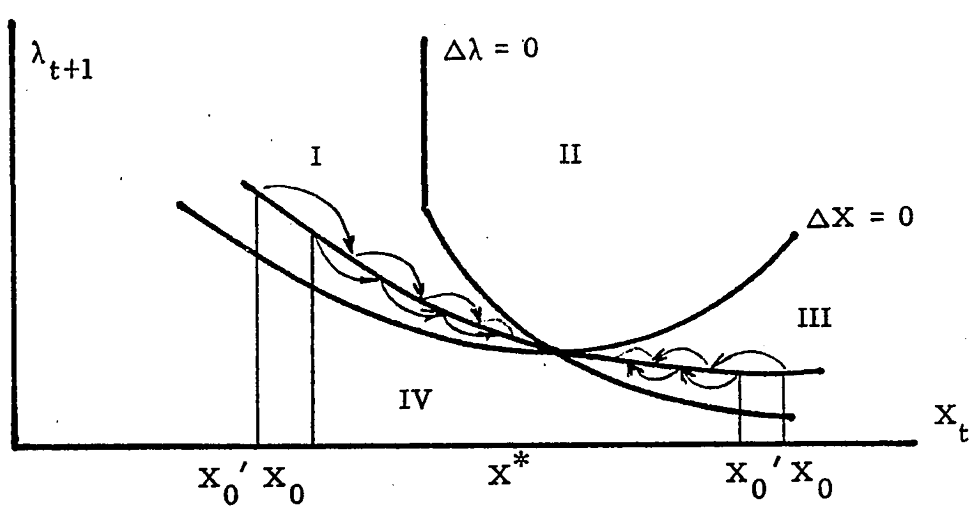

Figure III-4. Determining Locus of Optimal Points as a function of X_t is the locus of optimal points in Figure III-4. Thus the control problem becomes one of choosing the optimal "policy" for allocating effort depending only on the size of the population.

C. AN ANALYSIS AND COMPARISON OF OPTIMAL POLICIES DERIVED FROM THE DISCRETE MARKOV AND CONTROL THEORY MODELS

The purpose of this discussion is twofold. First, by comparing Markov and control theory policies we can determine the effects on optimal allocation schemes of discretizing the state and control variables. If the accuracy lost by employing a discrete model is small, the Markov model can safely be used to study optimal use of resources under conditions of uncertainty. Second, the general form of optimal deterministic policies are analyzed and summarized for subsequent use in comparison with stochastic decision rules derived in Chapter IV. An interesting result of this analysis is the possibility of optimal "cyclical fishing" for Classes III and VI. To my knowledge, only "steady state" fishing strategies that we found for Classes I, II, IV, and V have been discussed in the fishery economics literature.

C. 1. Comparison of Optimal Policies

Dynamic Programming and control theory solutions to the allocation problem in (17) are compared for Classes I, II, IV, and V to evaluate the accuracy of the discrete Markov model. The procedure for calculating optimal solutions using the Markov model is discussed in Appendix III-C. The method of control theory computations is presented in section B.4. of this chapter.

The Markov model performs quite well, yielding solutions nearly identical to the control theory results. For both models, optimal policy is to allocate effort so that the population tends towards a steady state gradually as in the Class II, IV, and V cases, or at a maximum rate as in the Class I programs.

Optimal steady state populations X^* derived by both models for various Class I, II, IV, and V cases appear in Table III-3. For Classes I and IV, where costs are zero, the results are reported for different values of the discount rate, in order to focus on the effect that varying preferences for consumption over time have on optimal allocation policies. To assess the impact of different cost conditions on optimal programs, Class II and V results are reported for various magnitudes of the cost parameter C_2.[19]

With both models, Classes (I and IV) and (II and V) have identical steady state populations. This occurs because optimal programs for classes with objective functions differing by a positive concave transformation converge to the same steady state, as we prove in Appendix III-D. The close agreement between the values of X^* for the two models indicates the accuracy of the Markov model. For every case reported in Table III-3 the Markov value of X^* falls within a range of ± 3.3% of the control theory value.

Table III-3. Comparison of Optimal Steady State Values

Program		Steady State Population (10^7 pounds)	
Class I, IV		Markov Model[20]	Control Model
B	Corresponding Annual Discount Rate		
0.9967	0.05	14.991	14.608
0.9906	0.10	13.998	14.310
0.9860	0.15	13.998	14.082
0.9819	0.20	13.998	13.878
0.9779	0.25	13.997	13.676
0.9745	0.30	13.972	13.504
Class II, V	B = 0.9906, C_1 = 500		
	C_2		
	0.02	18.965	19.007
	0.04	20.679	20.673
	0.06	21.965	21.881
	0.08	22.790	22.797

As expected for Classes I and IV, X^* increases with the discount factor B (although over a certain range the Markov value of X^* is insensitive to changes in B), since it is desirable to harvest less of the resource the higher society weights the consumption of future generations. With Classes II and V, X^* varies directly with C_2 as it becomes less profitable to fish for the resource as the cost of effort increases.

A comparison between Markov and control theory policies for certain of the Class I, II, IV, and V cases is presented in Tables III-4 - III-7. The first column in each table represents the current state of the fishery in terms of total population. For the Markov model, there are 31 states ranging in size from 0 to 30×10^7 pounds in multiples of 10^7 pounds. The optimal Markov and control theory allocations of effort corresponding to each state are listed in columns 2 and 3 respectively. The Markov effort allotments are limited to 250 multiples. Given the current state of the fishery and the corresponding effort allocation, column four lists the stock size next period for the Markov model calculated by equation (18). The resulting one period changes in population appear in column five. For a given initial state, the expected present value of the stream of returns yielded by the optimal effort policy for the Markov model is reported in column six. As expected, present value figures vary directly with the initial fishery state.

Looking at columns 2 and 3 of Tables III-4 - III-7, we observe the close similarity between Markov and control theory policies, particularly for Classes II and V. In each case with both models the population tends toward the same steady state as indicated in Table III-3, and at approximately the same rate. Although there is some discrepancy in the Markov and control theory effort allocations for the Class I program, the general form of the optimal program for the two models are alike. A most rapid approach path to equilibrium is indicated by the Markov policy (see column 4 of Table III-4) which we have seen is consistent with the control theory solutions. For this particular Class I case, larger values of effort for the Markov program occur because the population jumps to a smaller steady state with the Markov model than it does for the control theory model.

In conclusion, based on the results summarized in Tables III-3 - III-7, it appears that the optimal Markov and control theory policies are generally the same. Of course greater accuracy in the Markov solution is possible by increasing the number of states and policies in the model for a better approximation to a continuous system. However, the model performs satisfactorily for our purposes in that the Markov solution is not distorted or made artificial by using a discrete state and action system.

Table III-4. Optimal Markov and Control Theory Policies for Class I; B = 0.9906

State 10^7 Pounds	Markov E_t	Control Theory E_t	X_{t+1}	ΔX_t	V(X)
0	0	0	0.0000E 00	0.0000E 00	0.00000E 00
1	0	0	1.2954E 07	2.9535E 06	3.19413E 08
2	0	0	2.5700E 07	5.7000E 06	3.29675E 08
3	0	0	3.8240E 07	8.2395E 06	3.35163E 08
4	0	0	5.0572E 07	1.0572E 07	3.39023E 08
5	0	0	6.2698E 07	1.2698E 07	3.42090E 08
6	0	0	7.4616E 07	1.4616E 07	3.44713E 08
7	0	0	8.6328E 07	1.6328E 07	3.47023E 08
8	0	0	9.7832E 07	1.7832E 07	3.49106E 08
9	0	0	1.0913E 08	1.9130E 07	3.51018E 08
10	0	0	1.2022E 08	2.0220E 07	3.52806E 08
11	0	0	1.3110E 08	2.1104E 07	3.54496E 08
12	1750	0	1.4013E 08	2.0132E 07	3.56120E 08
13	12000	8969	1,4000E 08	1.0004E 07	3.57690E 08
14	20500	17666	1,3998E 08	-1.7500E 04	3.59229E 08
15	27500	25028	1,4019E 08	-9.8138E 06	3.60738E 08
16	33750	31304	1,4003E 08	-1.9974E 07	3.62215E 08
17	39000	36689	1.4001E 08	-2.9988E 07	3.63661E 08
18	43500	41326	1.4003E 08	-3.9974E 07	3.65076E 08
19	47250	45339	1.4025E 08	-4.9754E 07	3.66460E 08
20	50750	48817	1.4006E 08	-5.9938E 07	3.67814E 08
21	53750	51839	1.3995E 08	-7.0053E 07	3.69136E 08
22	56250	54467	1.4002E 08	-7.9984E 07	3.70427E 08
23	58500	56750	1.3994E 08	-9.0062E 07	3.71686E 08
24	60250	58734	1.4024E 08	-9.9759E 07	3.72915E 08
25	62000	60453	1.4006E 08	-1.0994E 08	3.74113E 08
26	63500	61940	1.3991E 08	-1.2009E 08	3.75280E 08
27	64500	63218	1.4038E 08	-1.2962E 08	3.76416E 08
28	65750	64311	1.3993E 08	-1.4007E 08	3.77520E 08
29	66500	65237	1.4022E 08	-1.4978E 08	3.78594E 08
30	67250	66014	1.4019E 08	-1.5981E 08	3.79637E 08

Table III-5. Optimal Markov and Control Theory Policies for Class II; B = 0.9906, C_1 = 500, C_2 = 0.06

State 10^7 Pounds	Markov E_t	Control Theory E_t	X_{t+1}	ΔX_t	V(X)
0	0	0	0.0000E 00	0.0000E 00	0.00000E 00
1	0	0	1.2954E 07	2.9535E 06	1.36545E 08
2	0	0	2.5700E 07	5.7000E 06	1.40932E 08
3	0	0	3.8240E 07	8.2395E 06	1.43278E 08
4	0	0	5.0572E 07	1.0572E 07	1.44928E 08
5	0	0	6.2698E 07	1.2698E 07	1.46239E 08
6	0	0	7.4616E 07	1.4616E 07	1.47360E 08
7	0	0	8.6328E 07	1.6328E 07	1.48348E 08
8	0	0	9.7832E 07	1.7832E 07	1.49238E 08
9	500	607	1.0878E 08	1.8776E 07	1.50056E 08
10	1250	1305	1.1924E 08	1.9239E 07	1.50820E 08
11	2000	2005	1.2938E 08	1.9377E 07	1.51541E 08
12	2750	2684	1.3919E 08	1.9190E 07	1.52227E 08
13	3500	3443	1.4868E 08	1.8678E 07	1.52884E 08
14	4250	4260	1.5784E 08	1.7841E 07	1.53515E 08
15	5000	5100	1.6668E 08	1.6680E 07	1.54125E 08
16	5750	5874	1.7519E 08	1.5194E 07	1.54716E 08
17	6500	6503	1.8338E 08	1.3383E 07	1.55291E 08
18	7250	7156	1.9125E 08	1.1248E 07	1.55850E 08
19	8000	8004	1.9879E 08	8.7875E 06	1.56396E 08
20	8750	8640	2.0600E 08	6.0025E 06	1.56929E 08
21	9500	9418	2.1289E 08	2.8928E 06	1.57453E 08
22	10000	10184	2.1989E 08	-1.1000E 05	1.57967E 08
23	11000	10928	2.2570E 08	-4.3010E 06	1.58468E 08
24	11750	11615	2.3162E 08	-8.3850E 06	1.58963E 08
25	12250	12350	2.3770E 08	-1.2303E 07	1.59449E 08
26	13250	13123	2.4247E 08	-1.7527E 07	1.59928E 08
27	13750	13813	2.4794E 08	-2.2056E 07	1.60401E 08
28	14500	14670	2.5258E 08	-2.7419E 07	1.60867E 08
29	15250	15353	2.5689E 08	-3.3107E 07	1.61327E 08
30	16000	16057	2.6088E 08	-3.9120E 07	1.61782E 08

Table III-6. Optimal Markov and Control Theory Policies for Class IV; B = 0.9906

State 10^7 Pounds	Markov E_t	Control Theory E_t	X_{t+1}	ΔX_t	V(X)
0	0	0	0.0000E 00	0.0000E 00	2.11966E 03
1	0	0	1.2954E 07	2.9535E 06	2.12650E 03
2	0	0	2.5700E 07	5.7000E 06	2.12672E 03
3	0	0	3.8240E 07	8.2395E 06	2.12684E 03
4	0	0	5.0572E 07	1.0572E 07	2.12692E 03
5	0	0	6.2698E 07	1.2698E 07	2.12699E 03
6	0	0	7.4616E 07	1.4616E 07	2.12704E 03
7	0	0	8.6328E 07	1.6328E 07	2.12709E 03
8	0	0	9.7832E 07	1.7832E 07	2.12714E 03
9	0	0	1.0913E 08	1.9130E 07	2.12718E 03
10	250	157	1.2002E 08	2.0024E 07	2.12722E 03
11	1500	4261	1.2981E 08	1.9808E 07	2.12725E 03
12	12500	10430	1.3001E 08	1.0005E 07	2.12729E 03
13	12000	15177	1.4000E 08	1.0004E 07	2.12732E 03
14	20500	18982	1.3998E 08	-1.7500E 04	2.12735E 03
15	23250	22404	1.4519E 08	-4.8094E 06	2.12738E 03
16	25750	25540	1.5007E 08	-9.9260E 06	2.12741E 03
17	27250	27841	1.5569E 08	-1.4308E 07	2.12744E 03
18	29500	29958	1.5981E 08	-2.0192E 07	2.12747E 03
19	34000	31998	1.6001E 08	-2.9992E 07	2.12750E 03
20	33000	33705	1.6793E 08	-3.2070E 07	2.12752E 03
21	35500	35154	1.7003E 08	-3.9968E 07	2.12755E 03
22	35750	36469	1.7542E 08	-4.4580E 07	2.12757E 03
23	36500	37534	1.7966E 08	-5.0341E 07	2.12759E 03
24	39000	38485	1.8028E 08	-5.9724E 07	2.12762E 03
25	40000	39824	1.8324E 08	-6.6763E 07	2.12764E 03
26	39000	39989	1.8992E 08	-7.0083E 07	2.12766E 03
27	41000	40616	1.9019E 08	-7.9812E 07	2.12768E 03
28	42500	41222	1.9104E 08	-8.8963E 07	2.12770E 03
29	40750	41657	1.9884E 08	-9.1158E 07	2.12771E 03
30	41750	42096	2.0024E 08	-9.9761E 07	2.12773E 03

Table III-7. Optimal Markov and Control Theory Policies for Class V; B = 0.9906, C_1 = 500, C_2 = 0.06

State 10^7 Pounds	Markov E_t	Control Theory E_t	X_{t+1}	ΔX_t	V(X)
0	0	0	0.0000E 00	0.0000E 00	2.11966E 03
1	0	0	1.2954E 07	2.9535E 06	2.12264E 03
2	0	0	2.5700E 07	5.7000E 06	2.12274E 03
3	0	0	3.8240E 07	8.2395E 06	2.12279E 03
4	0	0	5.0572E 07	1.0572E 07	2.12282E 03
5	0	0	6.2698E 07	1.2698E 07	2.12285E 03
6	0	0	7.4616E 07	1.4616E 07	2.12288E 03
7	0	0	8.6328E 07	1.6328E 07	2.12290E 03
8	0	0	9.7832E 07	1.7832E 07	2.12292E 03
9	500	607	1.0878E 08	1.8776E 07	2.12294E 03
10	1250	1305	1.1924E 08	1.9239E 07	2.12295E 03
11	2000	2005	1.2938E 08	1.9377E 07	2.12297E 03
12	2750	2684	1.3919E 08	1.9190E 07	2.12298E 03
13	3500	3443	1.4868E 08	1.8678E 07	2.12300E 03
14	4250	4260	1.5784E 08	1.7841E 07	2.12301E 03
15	5000	5100	1.6668E 08	1.6680E 07	2.12303E 03
16	5750	5874	1.7519E 08	1.5194E 07	2.12304E 03
17	6500	6503	1.8338E 08	1.3383E 07	2.12305E 03
18	7250	7156	1.9125E 08	1.1248E 07	2.12306E 03
19	8000	8004	1.9879E 08	8.7875E 06	2.12307E 03
20	8750	8640	2.0600E 08	6.0025E 06	2.12309E 03
21	9500	9418	2.1289E 08	2.8928E 06	2.12310E 03
22	10000	10184	2.1989E 08	-1.1000E 05	2.12311E 03
23	11000	10928	2.2570E 08	-4.3010E 06	2.12312E 03
24	11750	11615	2.3162E 08	-8.3850E 06	2.12313E 03
25	12250	12350	2.3770E 08	-1.2303E 07	2.12314E 03
26	13000	13123	2.4298E 08	-1.7017E 07	2.12315E 03
27	13750	13813	2.4794E 08	-2.2056E 07	2.12316E 03
28	14500	14670	2.5258E 08	-2.7419E 07	2.12317E 03
29	15000	15353	2.5746E 08	-3.2538E 07	2.12318E 03
30	16000	16057	2.6088E 08	-3.9120E 07	2.12319E 03

C.2. Optimal Fishing Strategies for Classes III and VI

The Markov model enables one to solve allocation problems of the Class III and VI variety where the objective function is not concave in the control variable. We have determined the optimal policies for certain of the Class III and VI cases, and they are presented in Tables III-8 and III-9.

Looking at columns 2 and 3 in each table, it is apparent that the population does not converge to an equilibrium unlike the previous classes. Instead, for large populations, effort allocation are large causing rapid depletion in the stock. As the population decreases all fishing is stopped and the stock is allowed to grow until it reaches a sufficiently large size to begin the harvest once again. This type of "cyclical" fishing takes advantage of the decreasing average cost of effort peculiar to Classes III and VI by employing large amounts of E_t whenever fish are harvested.

Changes in fishing strategy for different magnitudes of the cost parameter, C_3, are illustrated in Figures III-5 and III-6. For larger values of C_3 the fishing cycles are more pronounced. The minimum population where fishing begins is larger along with the size of the harvest and the amount of effort employed. With larger values of C_3 the average cost of effort at all levels of E_t increases. Consequently, to produce at the same average cost it is necessary to employ greater amounts of effort resulting in larger harvests and

Table III-8. Optimal Markov Policy for Class III; $B = 0.9906$, $C_3 = 100,000$

State 10^7 Pounds	E_t	X_{t+1}	ΔX_t	V(X)
0	0	0.0000E 00	0.0000E 00	0.00000E 00
1	0	1.2954E 07	2.9535E 06	2.54881E 08
2	0	2.5700E 07	5.7000E 06	2.63070E 08
3	0	3.8240E 07	8.2395E 06	2.67449E 08
4	0	5.0572E 07	1.0572E 07	2.70529E 08
5	0	6.2698E 07	1.2698E 07	2.72977E 08
6	0	7.4616E 07	1.4616E 07	2.75070E 08
7	0	8.6328E 07	1.6328E 07	2.76913E 08
8	0	9.7832E 07	1.7832E 07	2.78575E 08
9	0	1.0913E 08	1.9130E 07	2.80102E 08
10	0	1.2022E 08	2.0220E 07	2.81527E 08
11	0	1.3110E 08	2.1104E 07	2.82877E 08
12	0	1.4178E 08	2.1780E 07	2.84171E 08
13	0	1.5225E 08	2.2250E 07	2.85426E 08
14	0	1.6251E 08	2.2512E 07	2.86652E 08
15	0	1.7257E 08	2.2568E 07	2.87864E 08
16	0	1.8242E 08	2.2416E 07	2.89067E 08
17	0	1.9206E 08	2.2058E 07	2.90280E 08
18	0	2.0149E 08	2.1492E 07	2.91507E 08
19	74250	9.9976E 07	-9.0024E 07	2.92764E 08
20	76250	1.0003E 08	-9.9973E 07	2.94080E 08
21	78000	9.9971E 07	-1.1003E 08	2.95371E 08
22	79500	9.9864E 07	-1.2014E 08	2.96637E 08
23	80750	9.9765E 07	-1.3023E 08	2.97875E 08
24	81750	9.9735E 07	-1.4027E 08	2.99087E 08
25	87500	9.0019E 07	-1.5998E 08	3.00271E 08
26	87750	9.0418E 07	-1.6958E 08	3.01430E 08
27	88250	9.0042E 07	-1.7996E 08	3.02561E 08
28	88250	9.0479E 07	-1.8952E 08	3.03662E 08
29	88500	9.0139E 07	-1.9986E 08	3.04734E 08
30	88500	9.9143E 07	-2.0986E 08	3.05776E 08

Table III-9. Optimal Markov Policy for Class IV; $B = 0.9906$, $C_3 = 100,000$

State 10^7 Pounds	E_t	X_{t+1}	ΔX_t	V(X)
0	0	0.0000E 00	0.0000E 08	2.11966E 03
1	0	1.2954E 07	2.9535E 06	2.12468E 03
2	0	2.5700E 07	5.7000E 06	2.12484E 03
3	0	3.8240E 07	8.2395E 06	2.12492E 03
4	0	5.0572E 07	1.0572E 07	2.12498E 03
5	0	6.2698E 07	1.2698E 07	2.12503E 03
6	0	7.4616E 07	1.4616E 07	2.12507E 03
7	0	8.6328E 07	1.6328E 07	2.12511E 03
8	0	9.7832E 07	1.7832E 07	2.12514E 03
9	0	1.0913E 08	1.9130E 07	2.12517E 03
10	0	1.2022E 08	2.0220E 07	2.12520E 03
11	0	1.3110E 08	2.1104E 07	2.12523E 03
12	0	1.4178E 08	2.1780E 07	2.12525E 03
13	0	1.5225E 08	2.2250E 07	2.12528E 03
14	0	1.6251E 08	2.2512E 07	2.12530E 03
15	0	1.7257E 08	2.2568E 07	2.12533E 03
16	0	1.8242E 08	2.2416E 07	2.12535E 03
17	54000	1.1999E 08	-5.0006E 07	2.12537E 03
18	57500	1.2024E 08	-5.9756E 07	2.12540E 03
19	58500	1.2347E 08	-6.6533E 07	2.12542E 03
20	57250	1.2986E 08	-7.0143E 07	2.12544E 03
21	59750	1.3006E 08	-7.9944E 07	2.12547E 03
22	57250	1.3829E 08	-8.1711E 07	2.12549E 03
23	58500	1.3994E 08	-9.0062E 07	2.12551E 03
24	58000	1.4448E 08	-9.5520E 07	2.12553E 03
25	55000	1.5380E 08	-9.6200E 07	2.12555E 03
26	53750	1.5981E 08	-1.0019E 08	2.12557E 03
27	45750	1.8012E 08	-8.9880E 07	2.12559E 03
28	47500	1.8005E 08	-9.9953E 07	2.12561E 03
29	48500	1.8120E 08	-1.0880E 08	2.12562E 03
30	47250	1.8729E 08	-1.1271E 08	2.12564E 03

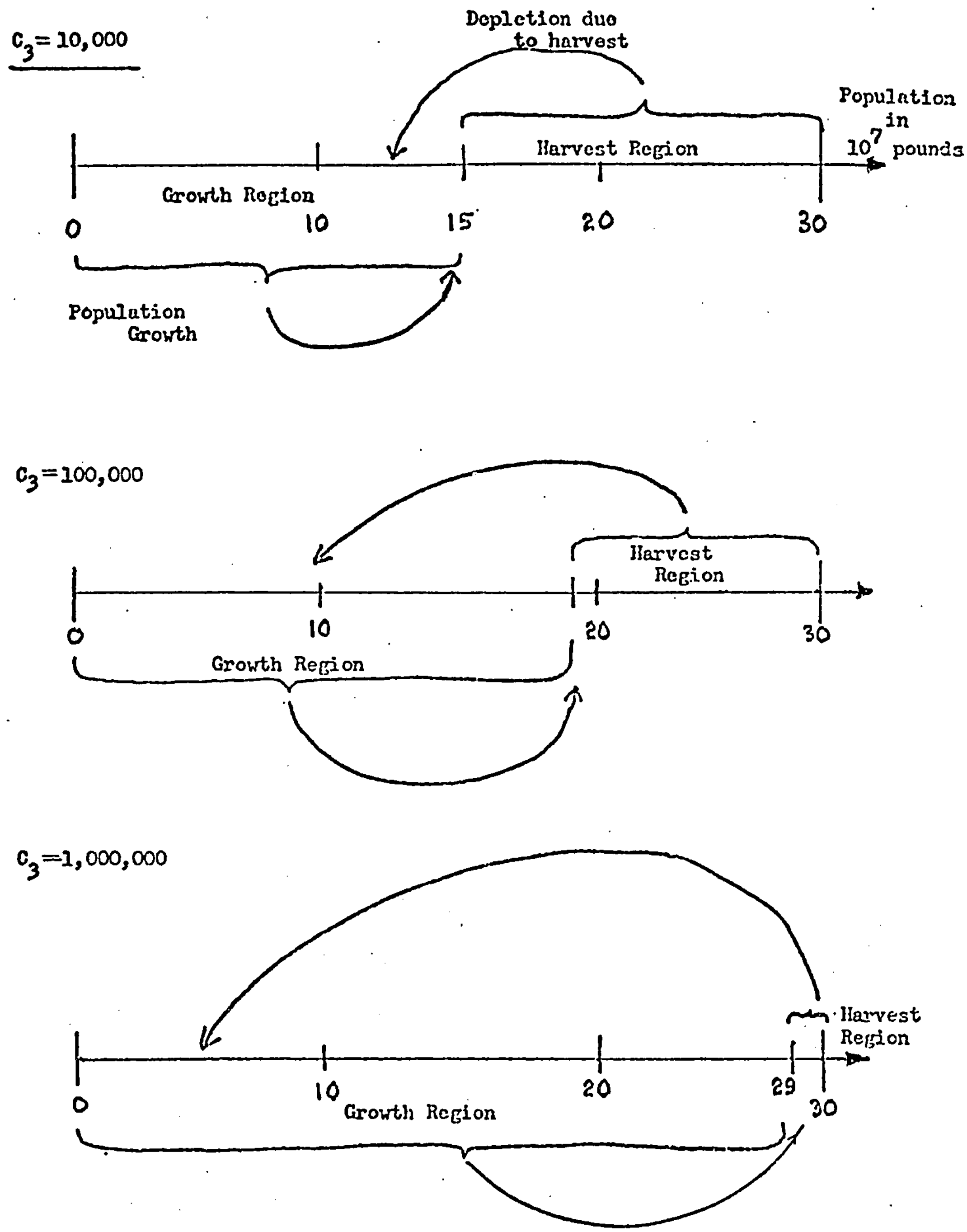

Figure III-5. Class III Fishing Policies

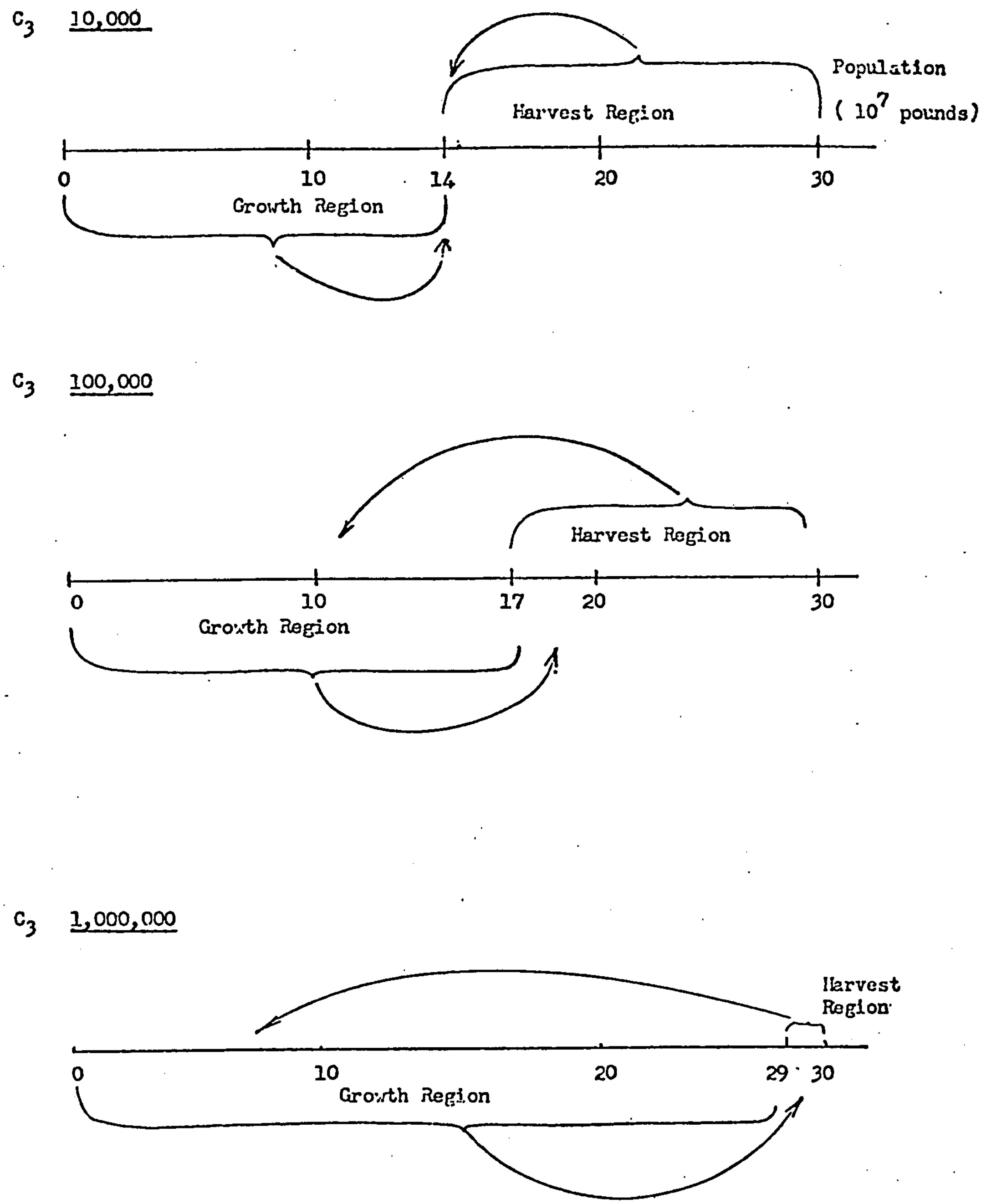

Figure III-6. Class VI Fishing Policies

greater fluctuations in the population. With smaller values of C_3, the opposite occurs and fluctuations in the population are less pronounced. Comparing Figures III-5 and III-6 we notice that the decreasing marginal utility of rents causes Class VI cyclical fishing to be less severe than Class III programs.[22]

Most management programs are based on "steady state" fishing. Usually an ideal steady state population is determined from biological and economic considerations. Then with a program of controlled resource use the population is allowed to converge to its optimal value. Although there is not always common agreement among economists and biologists as to the ideal value of the stationary population, the principle of steady state fishing is widely accepted.

The theoretical basis for steady state fishing comes from the control theory analysis of optimal fishing behavior. These models only yield solutions for certain specifications of the rent function which unfortunately preclude the possibility of economies of scale in supplying effort. Our results suggest that cyclical as opposed to steady state fishing is optimal for situations where there are decreasing average costs of supplying effort. Since there has been little estimation of cost functions for various fisheries, the case for steady state fishing may have arisen partially because of the analytical convenience of assuming convex cost functions for use in control theory analysis.

D. POLICY DISCUSSION

In Chapter IV, the foregoing analysis will be modified to allow for conditions of uncertainty. However, assuming for the present that the economic and biological processes of the fishery are non stochastic, what policy recommendations arise from our deterministic models of optimal resource use? We will focus on the results of Classes II and III. Class I programs are not applicable to the yellowfin tuna fishery since the cost of effort is not zero, and Classes IV - VI are only pertinent to the analysis of resource management under uncertainty. It is apparent that optimal allocation policies are sensitive to the specification of the cost of effort function. However, even without a specific knowledge of the cost structure, certain general conclusions can be inferred from our analysis.

The most important implication of our models is that the tuna Commission's policy of maximizing the sustainable physical yield from the fishery is generally not optimal. The policy is deficient in that it fails to specify the rate at which the fishery should approach its optimal steady state population, if it is initially displaced from it. However, even ignoring this problem, and assuming for the present that steady state as opposed to cyclical fishing is optimal, looking at Table III-3 we find that for Class II programs the stock tends towards a steady state size that generally differs from the maximum yield population of 14.7×10^7 pounds. Of course there is no reason to believe the two steady state populations will coincide since one population is based on maximizing the physical yield from the fishery, and the other is derived by maximizing the discounted economic benefit of the resource.[23]

Although the inefficiencies of the maximum yield policy have been discussed repeatedly in the literature,[24] the policy is still retained by most fishery commissions because it is deemed to be "workable." Proponents of the policy argue that if under the optimal economic program the stock converges to a steady state size close to the maximum sustainable yield population, then the maximum yield policy should be adopted since it is probably easier for managers to follow and to understand. Considered pragmatically, the argument is appealing although it rests primarily on two assumptions that require further consideration.

First, the discrpeancy between optimal economic steady state populations and the maximum yield population may not be small as we assumed above. Looking at Table III-3, the steady state stocks X^* for Class II may be considerably greater than the maximum sustainable yield population, particularly as costs increase. From the standpoint of economic efficiency, the allocation of effort and the resulting annual catch are excessive under the maximum yield policy and they should be reduced allowing the population to reach its optimal level at X^*. As a political matter however, such a program of effort reduction may be very difficult to introduce given the current regulatory policy in the Eastern Pacific yellowfin tuna fishery. Historically the Commission has adhered to an annual catch quota by restricting the season during which fishing is allowed. This system only regulates the size of the catch, but not the number of vessels operating in the fishery. As a result, the fishery has become vastly over capitalized. The current size of the tuna fleet is much greater than the number of ships required to catch the annual quota efficiently.[25] The Commission also grants special quotas to lesser developed countries with relatively small fishing fleets. Recently, the demand for special quotas has increased to allow the developing fishing countries such as Mexico to build a larger and more modern fleet, and to accommodate new countries wishing to enter the fishery. In light of this increased competition among countries for quota shares, and the fact that there is already excess capacity in the fleet, it seems unlikely that a program designed to reduce the allocation of effort and the resulting total annual catch would be well received.

One alternative to the current system would be to reduce the size of the fleet, the allocation of effort, and the annual catch through the sale of a limited number of licenses. Presumably if the licenses were sold competitively, only the most efficient ships could afford to fish and the proceeds from the licenses could be used to compensate those boats forced out of the fleet.[26]

The second major assumption behind the argument for choosing a maximum sustained yield policy is that steady state fishing is optimal. However, our results for Class III suggest that cyclical as opposed to steady state fishing is optimal for situations where there are decreasing average costs of supplying effort. Presumably under these conditions, the fleet would fish intensively for yellowfin tuna over a short period of time, then move on to other fisheries, returning to the tuna fishery once the stock had replenished itself. In this way, the stock size would fluctuate within certain limits, depending on the cost conditions, in the manner depicted in Figure III-5.

In conclusion, we suggest that the current policy of maximizing the sustainable physical yield from the yellowfin tuna fishery is generally not optimal from the viewpoint of economic efficiency. Arguments for the policy stem from the belief that it is easier to understand and more readily accepted by the decision making hierarchy than alternative programs. If this is true, the administrative advantages of the maximum yield policy need to be compared with the loss in economic rents from the fishery that are incurred by adopting this program. Where there is a wide discrepancy between the optimal economic maximum sustained yield programs, the loss in economic rents may be quite large.

One group of fishery economists maintain that whatever difference there may be between optimal economic and maximum sustained yield policies is likely to be swamped by the uncertainty existing with regard to the population dynamics of the fishery. This contention will be examined in more detail in Chapter IV.

APPENDIX III-A

Estimation of the Yellowfin Demand Curve

Most of the yellowfin tuna purchased by U.S. canneries comes from the Eastern Pacific fishery. Table III-10 shows the U.S. price of raw yellowfin and the annual catch of yellowfin from the Eastern Pacific for the years of 1958-1972. Prices were relatively stable from 1958 until 1966 when they increased significantly. Since then they have fluctuated betwee 13 and 17 cents per pound.

For the Eastern Pacific yellowfin fishery we hypothesize that the price is not influenced by the size of the total catch. This is because the price of tuna is determined on the world market and the

Table III-10. Catches and Prices of Yellowfin Tuna from 1958-1972

Year	Yellowfin Catch in the Eastern Pacific (millions of pounds)	Real Price per[27] Pound (1956 dollars)
1958	148.4	0.130
1959	140.5	0.125
1960	244.3	0.120
1961	230.9	0.123
1962	174.1	0.146
1963	145.5	0.127
1964	203.9	0.124
1965	180.1	0.132
1966	182.3	0.167
1967	179.3	0.128
1968	229.1	0.138
1969	252.8	0.138
1970	283.5	0.148
1971	226.3	0.167
1972	304.1	0.166

quantity of yellowfin taken from the Eastern Pacific is only a small fraction of the total world supply of tuna. Using ordinary least squares and the price and landings data in Table III-10 for 1958-1972 we tested this hypothesis by estimating the following equation expressing price, p, as a function of the total landings, X, and time, t.

$$p = \underset{(8.00)}{12.6} - \underset{(-0.04)}{0.0034\,X} + \underset{(2.71)}{0.29\,t} \qquad (48)$$

$$F = 5.98 \qquad D.W. = 2.096$$

The t statistics appear in the parenthesis directly below each of the estimated coefficients. The coefficient for landings is not significant; this confirms our hypothesis that prices are not affected by landings. The time coefficient, which was significant and positive, presumably measures the increase in price caused by population growth and better living standards. Despite this, the time trend for prices is difficult to predict. The primary increase in price is only between two periods, (1958-1965) and (1966-1972), with no systematic price increases occurring within each period.

Based on these results, price is assumed to be independent of total landings with p = \$0.15, the mean price during the 1966-1972 period. While our model allows for random variations in price, the mean price level is assumed to be constant. In Chapter II, we suggest modifications in the present model that incorporate systematic increases or decreases in the price level over time.

APPENDIX III-B

Determination of G

In Chapter IV, R is a random variable given by

$$R(X_t, E_t) = p(\eta_2 k X_t E_t) - C(E_t) \tag{49}$$

where η_2 is a random variable with $\mathcal{E}(\eta_2) = 1$. A lower bound for R is $-C(E_t)$ which occurs for $\eta_2 = 0$. If $R + G > 0$ for all R then G must be greater than the maximum value of $C(E_t)$. An upper bound for $C(E_t)$ is determined as follows: A necessary condition for $E_t > 0$ is that

$$\mathcal{E}(U(R + G)) - U(G) > 0 \tag{50}$$

Now $U(\mathcal{E}(R) + G) > \mathcal{E}U(R + G))$ since $U = \ln(R + G)$ is strictly concave. Thus

$$U(\mathcal{E}(R) + G) - U(G) > \mathcal{E}U(R + G) - U(G) > 0 \tag{51}$$

which implies

$$pkX_tE_t - C(E_t) > 0 \tag{52}$$

since $U' > 0$. In particular,

$$\bar{\Delta}pkX_tE_t - \bar{\Delta}C(E_t) > 0 \tag{53}$$

so that in any time period with $E_t > 0$, the expected revenue from the harvest must exceed the costs of production. In section A. 3. a. we specify that the largest possible population in the fishery is denoted by X_{30}, where $X_{30} = 30 \times 10^7$ pounds. Clearly the maximum catch cannot exceed the maximum population, X_{30}, so that an upper bound for total revenue is

$$pX_{30} = (\$0.15)(30 \times 10^7) = 4.5 \times 10^7$$

From equations (53) and (54) we obtain

$$4.5 \times 10^7 \geq p\bar{\Delta}kX_tE_t > \bar{\Delta}C(E_t) \quad , \qquad (55)$$

and that therefore an upper bound (not necessarily least upper bound) for $C(E_t)$ is 4.5×10^8, which determines the value of G.

APPENDIX III-C

Description of the Markov Decision Program

The computer program used to find the computational solution for Classes I - VI is described in this section. The program implements Howard's Algorithm (see Appendix II) to select the optimal policy for allocating effort in the fishery. The algorithm involves calculating the present value of the stream of economic rents accruing to the fishery for a given policy and then determining a better policy if one exists by using a policy improvement routine. A flow chart for the program is presented in Figure III-7. Each procedure follows in the order indicated by the numbers 1 - 14, and an explanation of each step is given below. The program was written in ALGOL and is designed to run on the Burroughs 6700 at the University of California, San Diego. A complete listing of the program may be obtained from the author.

1. Program begins.

2. The values for the parameters, a, b, C_1, C_2, C_3, B, k, p, and G are read into the program.

3. There are 31 possible states stored in the one dimensional array denoted by X[I]; I = 0, 1, 2, ..., 30. Each state corresponds to a certain population size given by $X[I] = I \times 10^7$ pounds. X[0] represents the minimum stock of 0 pounds and X[30] is the largest

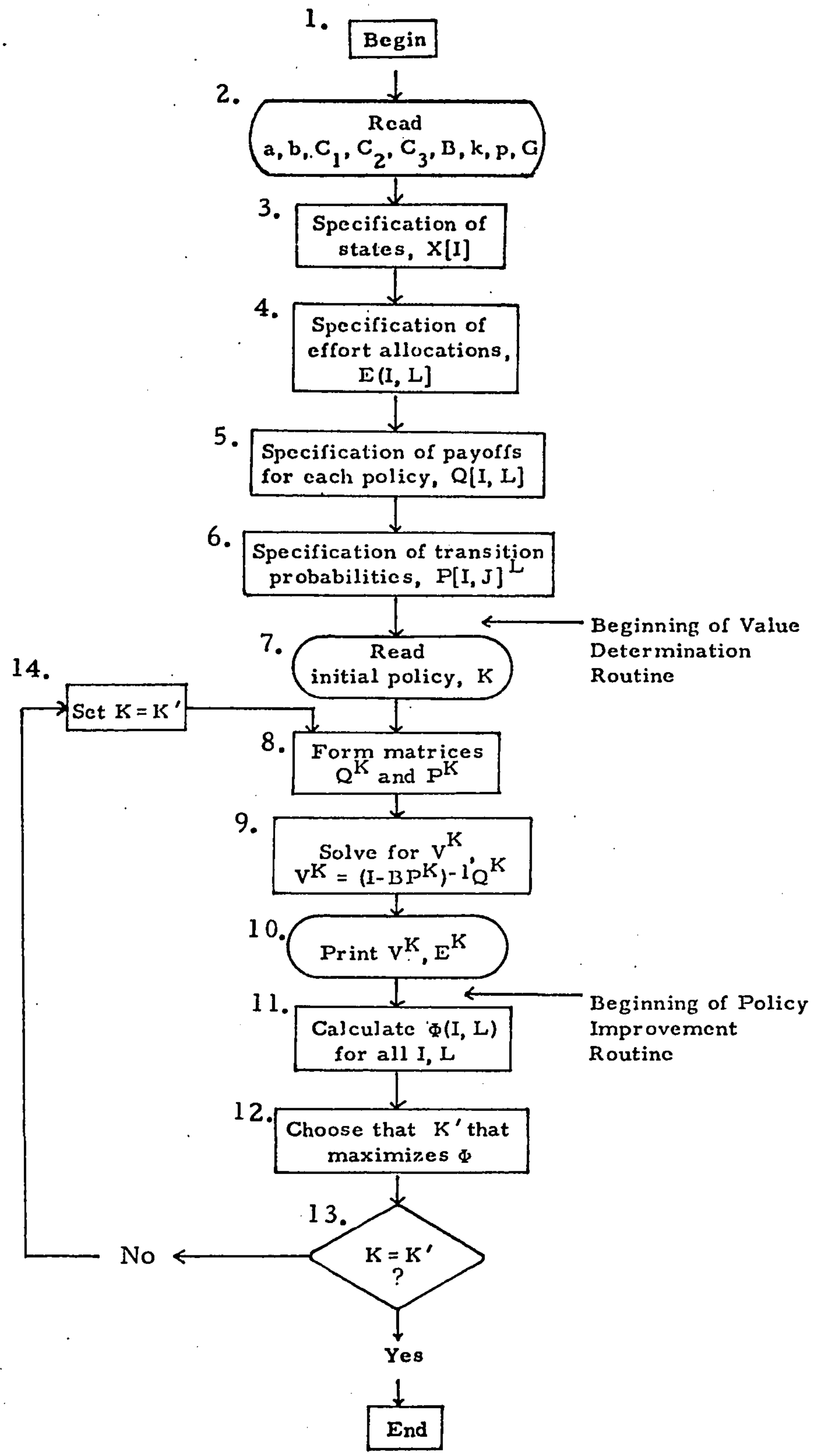

Figure III-7. Flow Chart

possible population. X[30] is greater than the maximum sustainable stock, 29.4×10^7 pounds and thus is large enough to include all probable values that the stock may assume.

4. In each state there are a finite number of possible effort allocations. Each allocation is stored in the two dimensional array, E[I, L] where I represents the state and L is an index of the amount of effort used (measured in terms of boat days at sea). The effort allocations are expressed as multiples of 250 boat days ranging from a minimum of 0 days to a maximum amount which is determined by the economic or technological constraints for each case considered. For example, the maximum effort allocation will obviously never exceed the rate of effort which maximizes the immediate returns from the fishery, i.e.

$$E_t \leq E_M \quad \text{where } E_M \text{ is defined by } \quad \frac{\partial E(X_1 E_t)}{\partial E_t} = 0 \, .$$

However, $E_t < E_M$ if there are technological limits on the maximum amount of effort which can be used during a given time interval.

5. In each state, I, the payoff or utility from the effort allocation L, is stored in the 2-dimensional array, Q[I, L] where

$$Q[I, L] = U(R(X[I], E[I, L]))\bar{\Delta}$$

and R is the rate at which rents accrue to the fishery and $\bar{\Delta}$ is the length of each time interval.

6. The transition probability of moving from state $\underline{I}$ to state $\underline{J}$ in one time period if the effort allocation during the interval is $E[I, L]$ is stored in the two dimensional array denoted by $P[I, J]^{L}$. The method for computing these transition probabilities is discussed in section C.4. of Chapter II.

7. At this stage the states, effort allocations, payoffs, and transition probabilities have been specified and stored in the computer's memory system, and we are ready to begin the Value Determination Routine (see Appendix II). The initial policy K is read into the program. A policy is a rule for selecting an effort allocation in each state. Thus K is a 1×31 row vector, $K = [k_0, k_1, k_2, \ldots, k_{30}]$ where the i^{th} entry specified the effort allocation for the i^{th} state. The entries of K are selecting according to reasonable guesses about the optimal amount of effort to allocate in each state.

8. The column vector Q^K and matrix P^K to be used in step 9 are formed by selecting elements $Q[I, K_I]$ and $P[I, J]^{K_I}$ respectively from the memory storage for all $I, J = 0, 1, 2, \ldots, 30$.

9. A procedure for solving systems of linear equations called FORMOPAK, available from the U.C.S.D. computing center, is used to solve a system of 31 equations in 31 unknowns, $V[I]^K$; $I = 0, 1, 2, \ldots, 30$, where the system is given by,

$$\begin{bmatrix} V^K[0] \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ V^K[30] \end{bmatrix} + B \begin{bmatrix} P[0,0]^{K_0} & \cdots & P[0,1]^{K_0} & \cdots & P[0,30]^{K_0} \\ \cdots\cdots & & P[1,1]^{K_1} & \cdots & \vdots \\ \vdots & & & \ddots & \vdots \\ P[30,0]^{K_{30}} & & \cdots\cdots & & P[30,30]^{K_{30}} \end{bmatrix} \begin{bmatrix} V^K[0] \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ V^K[30] \end{bmatrix}$$

$$= \begin{bmatrix} Q[0,K_0] \\ Q[1,K_1] \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ Q[30,K_{30}] \end{bmatrix}$$

$V[I]^K$ is the present value of the economic returns to the fishery for policy K assuming the initial stock equals X[I].

10. The values of $V[I]^{K_I}$, $E[I,K_I]$ are printed for $I = 0, 1, 2, \ldots, 30$.

11. The Policy Improvement Routine begins by calculating the quantity,

$$\Phi[I,L] = Q[I,L] + B \sum_{j=0}^{30} P[I,J]^L \; V[I]^K$$

12. A new policy K' is formed by selecting the effort allocation in each state, $\underline{I}$, that maximizes $\Phi[I, L]$ for all possible $\underline{L}$.

13. The new policy K' is compared to the previous policy K. If K' and K are identical then by the convergence property of the Howard Algorithm K is the optimal policy and the program ends; otherwise the program returns for another iterative cycle beginning at step 14.

14. K' becomes the new policy for the Value Determination Routine and steps (8-14) are repeated until the optimal policy is determined.

APPENDIX III-D

Steady State Properties

Consider the problem

$$\max_{E_t} \sum_{t=0}^{\infty} B^t\, U(R(X_t, E_t))\, \bar{\Delta} \tag{54}$$

subject to

$$X_{t+1} = X_t + [(a - bX_t)X_t - kX_tE_t]\,\bar{\Delta};\ \ X_0 = \bar{X} \tag{55}$$

Assume the solution to (54) indicates that the optimal program converges to the same steady state (X^*, λ^*, E^*) for all initial stocks X_0 defined by the conditions

$$U' \frac{\partial R}{\partial E} - B\,\lambda^* kX^* = 0 \tag{56}$$

$$\Delta X_t = ((a - bX^*)X^* - kX^*E^*)\,\bar{\Delta} = 0 \tag{57}$$

$$\Delta \lambda_t = -U' \frac{\partial R}{\partial X} - B\,\lambda^* \left(a - 2bX^* - \frac{1 - B}{\bar{\Delta} B} - kE^*\right) = 0 \tag{58}$$

Clearly the solution to

$$\begin{aligned} &\operatorname*{Max}_{E_t} \sum_{t=0}^{\infty} B^t[k_1 U(R(X_t, E_t)) + k_2]\,\bar{\Delta};\ \ k_1, k_2 \text{ constants, } k_1 > 0 \\ &= \max_{E_t}\ k_1 \sum_{t=0}^{\infty} B^t\, U(R(X_t, E_t))\,\bar{\Delta} + \frac{k_2 \bar{\Delta}}{1 - B} \end{aligned} \tag{59}$$

subject to (55) is identical to the solution to (54). Solutions are invariant to positive linear transformations of the objective function. Consider the problem

$$\max_{E_t} \sum_{t=0}^{\infty} B^t [\phi(U(R(X_t, E_t) + K_2)]\bar{\Delta}; \quad \phi' > 0 \tag{60}$$

subject to (55), where ϕ is a concave function. Generally solutions to (54) and (60) will not coincide; however, we can show that the optimal steady state values of X^* are identical. For (60) a stationary equilibrium occurs for values of X^*, λ^*, and E^* satisfying the three equations:

$$\phi' U' \frac{\partial R}{\partial E} - B\lambda^* kX^* = 0 \tag{61}$$

$$\Delta X_t = ((a - bX^*)X^* - kX^*E^*)\bar{\Delta} = 0 \tag{62}$$

$$\Delta\lambda_t = -\phi' U' \frac{\partial R}{\partial X} - B\lambda^*\left(a - 2bX^* - \frac{1-B}{\bar{\Delta}B}\right) - kE^* = 0 \tag{63}$$

Since solutions are insensitive to positive linear transformations of the objective function we may arbitrarily set $\phi'(U(R(X^*, E^*))$ equal to one in the equations above. Now it is obvious that these equations also define a steady state equilibrium for (54) as well. One can also show that the optimal program for problem (60) converges to the steady state (X^*, λ^*, E^*) for all initial stock X_0.

Footnotes

[1]For a discussion of the Commission's policy in regard to setting quotas, see the Annual Report of the Inter-American Tropical Tuna Commission, 1966-1974.

[2]The formulation of this model appears in Schaefer (1957).

[3]In order to be consistent with the rest of this chapter, the equations appearing in this section are written in discrete form, although these equations most often appear in continuous form in the references that I have cited.

[4]The "fishable stock" includes all of those fish that are of sufficient size and age for capture by the fishery.

[5]Without dealing specifically with the determinants of growth, new "recruitment," existing population "growth," "fishing mortality," and "natural mortality," equation (5) is an aggregate description of a commercial fishery. It is beyond the scope of this discussion to mention conditions under which (5) is a good approximation to the dynamics of an exploited population. However, these conditions are examined thoroughly in Beverton and Holt (1957, pp. 329-30), and Schaefer (1957).

[6]The difficulties of obtaining costs of operation data from coat owners is discussed in Green and Broadhead (1964).

[7]For example, a large portion of the costs of operation reported by owners is the labor bill. The crew is paid a fixed percentage of the total value of the catch; see Green and Broadhead (1964). In accounting terms, labor costs vary with the value of the catch, while the opportunity cost of labor is presumably insensitive to this value.

[8]Another example where the cost of effort might be zero is in the case of sport fishing where people fish for the sake of relaxation and enjoyment.

[9]For a description of the purse seine fishing technology, see Green, Perrin, and Petrich (1971).

[10]Recently the Commission has increased catch quotas to allow the population to reach a smaller size. This was done to obtain more information on the population dynamics of the stock.

[11] For the Schaefer model, the population producing the maximum sustained yield, is one half the size of the maximum sustainable population.

[12] Unless E_{max} is given by technological constraints, it is logically determined by the following restriction on the total catch during each time period. Clearly, the total catch cannot exceed the size of the stock available at the beginning of the period, i.e.

$$\bar{\Delta} k X_t E_t \leq X_t$$

implying that $E_t \leq \frac{1}{\bar{\Delta} k} = E_{max}$.

[13] The necessary conditions set forth by the Maximum Principle of Pontryagin are discussed in Pontryagin et al. (1962) and Lee and Marcus (1967). A discussion of the discrete maximum principle is found in Halkin (1966) and Fan and Wang (1964).

[14] See Intrilligator (1971).

[15] $\Delta X_t = \frac{X_{t+1} - X_t}{\bar{\Delta}}$, and $\Delta \lambda_t = \frac{\lambda_{t+1} - \lambda_t}{\bar{\Delta}}$,

[16] In equations (30) and (31), $E_t = E_t(X_t, \lambda_{t+1})$ to emphasize that E_t is a function of X_t and λ_{t+1}.

[17] If $\frac{1 - B}{\bar{\Delta} B} > a$, then it is optimal to deplete the stock to the point where the immediate profit from further harvesting is negative. If an immediate profit can be made from harvesting the last remaining animals, then it is optimal to drive the population to extinction; see Clark (1973).

[18] Because $(X^* \lambda^*)$ is a saddle point only one path converges to the stationary equilibrium. Since the path never reaches $(X^* \lambda^*)$ one can never confirm whether or not he has located the convergent path. However, arbitrarily close approximations to the optimal path can be achieved by determining "reasonably convergent" paths. For our purposes, paths which come within one thousandth of one percent of the value of X^* without leaving regions I and III are considered reasonably convergent.

[19]The values used for the biological parameters in each program we analyzed correspond to the figures reported in Table III-1. For the economic parameters, $p = \$0.15$, $C_1 = \$500$, and $G = 4.5 \times 10^8$. The values assumed for C_2, C_3 and B are specified with the results for each case.

[20]To compute the steady state population for the Markov model we first obtain optimal effort levels as a function of the states. Effort allocations for populations falling between two states are calculated by linear interpolation. A steady state is then determined by finding the population for which the optimal allocation of effort and the level of effort necessary to maintain the population at its current size coincide.

[21]Note that the control theory effort allocations reported are the same for Classes II and V. Calculating the optimal paths for population and effort for Class V programs is quite difficult requiring the repeated solution to a 7th order polynomial in E_t. To simplify the procedure we approximated E_t with the optimal effort allocation derived for the Class II case. The approximation was excellent for Class V yielding optimal paths for X_t and λ_{t+1} that were reasonably convergent.

[22]In fact, for relatively small values of C_3 the cycles decrease and the optimal policy degenerates into a steady state fishing strategy. For example, see the Class VI program in Figure III-6 for $C_3 = 10,000$.

[23]It is not surprising to find that steady state stocks for Class I are quite close to the maximum sustained physical yield population of 14.7×10^7 pounds. Since the costs of effort are zero, maximizing the physical yield from the fishery is nearly identical to maximizing the discounted stream of economic rents.

[24]In particular, see Christy and Scott (1965).

[25]An indication of the dramatic increase in the fleet and in the competition among fishermen for yellowfin is reflected in the fact that the length of the legal fishing season has decreased from nine months to three months in the last ten years.

[26]A complete discussion of various regulatory programs that might be applied in the Eastern Pacific yellowfin tuna fishery is beyond the scope of this study. However, for a good discussion of fishery regulation in general, see Christy and Scott (1965), Coase (1969), and Scott (1969).

[27]Real prices in terms of 1956 dollars are obtained by dividing the current price of tuna by the wholesale price index for all commodities where 1956 = 100.

[28]Data on the catch of yellowfin in the Eastern Pacific was obtained from the Annual Report of the Inter-American Tropical Tuna Commission, 1972.

[29]Data on current yellowfin prices was obtained from Historical Statistics, U.S.F.W.S., Bureau of Commercial Fisheries and Market News, U.S. Dept. of Commerce.

[30]The wholesale price index was obtained from the Economic Report of the President, 1973.

Chapter IV

A STOCHASTIC MODEL OF THE FISHERY

A. INTRODUCTION

From the literature on optimal resource allocation under stochastic conditions, our model is most closely related to the important contributions of Leland (1974), Brock and Mirman (1972), Levhari and Srinivasan (1966), and Phelps (1962). These analyses deal with the problem of finding optimal consumption or investment policies from the point of view of an individual or a single sector economy (in the case of Brock and Mirman), when the rate of growth of the capital stock is random. For the case of an ocean fishery, we are interested in determining the optimal resource consumption strategies where the capital stock is represented by the size of the fish population.

There are two aspects of our model distinguishing it from previous analysis. First, with a given allocation of fishing effort, the total value of the resource consumed is random, varying either with fluctuations in the catch rate or changes in the market value of output. In the papers mentioned above, consumption is non random and completely determined by the decision maker. Second, the net value of consumption in the fishery is the value of the catch minus the cost of effort. The net value not only varies with the catch but also depends on the stock since the effort required for a given catch decreases with population. In contrast, the net value of consumption is independent of the stock in standard models of capital accumulation. Because of this second difference, the standard techniques appearing in the literature to solve for optimal consumption policies are not applicable to our analysis. However, with the Markov Decision Process model developed in Chapters II and III, we can characterize optimal allocation programs in the fishery using numerical methods.

A.1. Questions Concerning the Effect of Uncertainty on Optimal Resource Allocation

The following questions will be of particular interest to us in analyzing these programs:

1. How do different attitudes toward social risk bearing as regards variations in resource rents, affect optimal decision rules when there is uncertainty about:

   a. Consumer demand for the fishery products,

   b. The rate of resource depletion (for given effort allocations), and the rate of natural growth of the population?

2. What is the effect of increased uncertainty about consumer demand, and growth and depletion rates on optimal programs?

3. Is it possible to account for the social attitudes towards risk bearing in the social discount rate?

4. What are the practical policy implications for the Eastern Pacific yellowfin tuna fishery obtained from analyzing the effect of uncertainty on optimal resource allocation in the fishery? Are decision rules for resource consumption derived by assuming

deterministic conditions in the fishery appropriate in a stochastic environment? Which economic and biological parameters are crucial in determining optimal programs, and what data are needed to estimate these parameters accurately?

Analyzing these questions will provide us with a convenient means of organizing and discussing the results we have obtained. However, before beginning our discussion it would be helpful to describe and list the programs included in our study.

A. 2. Description of Cases

Each of the cases analyzed simulates a different set of conditions in the fishery. These programs are characterized by the kind of cost conditions for effort, by the types of stochastic variation in the economic and biological parameters, and by the social attitudes toward risk assumed in the model.

The resource allocation problem in each case is to

$$\underset{E_t}{\text{maximize}} \sum_{t=0}^{\infty} B^t \, \mathcal{E}\, U[R(X_t, E_t)] \bar{\Delta}$$

$$\text{subject to} \quad X_{t+1} = X_t + [\eta_{1t}(a - bX_t)X_t - \eta_{2t} kX_t E_t] \bar{\Delta}$$

The notation and designation of variables employed here is consistent with that used in Chapter III. Recall that $\mathcal{E}$ represents the expectation operator, and η_{1t} and η_{2t} are the growth and depletion rate parameters respectively.

Solutions to the allocation problem are characterized for the cases listed in Table IV-1. For convenience we will refer to a particular program by the label corresponding to it in the table. The Roman numerals in each label refer to the specification of the utility and rent functions, reflecting the cost conditions and attitudes toward risk bearing that prevail in the fishery. The letters indicate the type of stochastic variation in the model, for which we assume there are four possibilities. In the yellowfin tuna and other fisheries[1] fluctuations in the consumer demand and changes in the availability of substitute food products cause the price of the resource to vary. To assess the impact of these variations on resource allocation we consider cases where price is random, denoted by the letter P in the labels appearing in Table IV-1. Because of changes in environmental conditions, the rate of fish landings (for a given allocation of effort), and the natural rate of growth of the stock may fluctuate. Therefore, we also include situations where the depletion rate is variable, denoted by $\underline{D}$; where depletion and growth rates are random and completely dependent, denoted by $\overline{\underline{DG}}$; and where they are independent, denoted by $\underline{DG}$. Summarizing, the programs listed in Table IV-1 are derived by permuting each of the six specifications of U(R) with the four kinds of stochastic variation in the model.

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[1] See footnotes on pages 252-253.

Table IV-1. List of Cases

Stochastic Variation / $U(R(X_t, E_t))$	Random Prices η_{1t}, η_{2t} Non Random	Random Depletion Rates η_{1t}, p_t Non Random	Random Growth and Depletion Rates (Complete Dependence) p_t Non Random	Random Growth and Depletion Rates (Complete Independence) p_t Non Random
$p_t \eta_{1t} kX_t E_t$	I-P	I-D	I-$\overline{DG}$	I-DG
$p_t \eta_{1t} kX_t E_t - C_1 E_t - C_2 E_t^2$	II-P	II-D	II-$\overline{DG}$	II-DG
$p_t \eta_{1t} kX_t E_t - C_3 E_t^{1/2}$	III-P	III-D	III-$\overline{DG}$	III-DG
$Ln(G + p_t \eta_{1t} kX_t E_t)$	IV-P	IV-D	IV-$\overline{DG}$	IV-DG
$Ln(G + p_t \eta_{1t} kX_t E_t + C_1 E_t + C_2 E_t^2)$	V-P	V-D	V-$\overline{DG}$	V-DG
$Ln(G + p_t \eta_{1t} kX_t E_t - C_3 E^{1/2})$	VI-P	VI-D	VI-$\overline{DG}$	VI-DG

A.3. Frequency Distributions for Random Variables

The frequency distributions for the random variables in our model, price, p_t, the depletion parameter, η_{2t}, and the growth parameter, η_{1t}, are not known because of a lack of data.[2] Therefore, we make the following assumptions: All random variables are distributed independently over time. For computational convenience, in the $\overline{DG}$ cases we assume η_1 and η_2 are identical. The expected value of the variables is equal to the value they assume under deterministic conditions with $\mathcal{E}(p_t) = \$0.15$, and $\mathcal{E}(\eta_1) = \mathcal{E}(\eta_2) = 1$.

We are able to simulate a rich variety of stochastic conditions in the fishery by assuming that the variables have either a truncated triangular or uniform frequency distribution. Like the uniform distribution, the truncated triangular distribution is completely determined by the specification of two range parameters, assuming the distribution mean is fixed. For instance, the distribution, $h(\eta_{1t})$, for η_{1t}, an example of which appears in Figure IV-1, is constructed in the following manner:

> For all values of d_1 and d_2, which specify the range of the distribution, with $0 \le d_1 < 1 < d_2$, the frequency function for η_{1t} is completely determined by the two conditions:

$$\mathcal{E}(\eta_{1t}) = 1 \tag{2a}$$

$$\left.\begin{array}{lll} h(d_1) = 0 & \text{if} & (1 - d_1) > (d_2 - 1) \\ \begin{array}{l} h(d_1) \\ h(d_2) \end{array} = 0 & \text{if} & (1 - d_1) = (d_2 - 1) \\ h(d_2) = 0 & \text{if} & (1 - d_1) < (d_2 - 1) \end{array}\right\} \tag{2b}$$

The distribution is symmetric when $(1 - d_1) = (d_2 - 1)$ or skewed when the equality doesn't hold. Truncated triangular distributions for the other two parameters, p_t, and η_{2t} are constructed similarly. Hopefully, determining the effect on resource allocation for different distributions of p_t, η_{1t}, and η_{2t} will help to indicate what empirical information on these random variables is needed for fishery management.

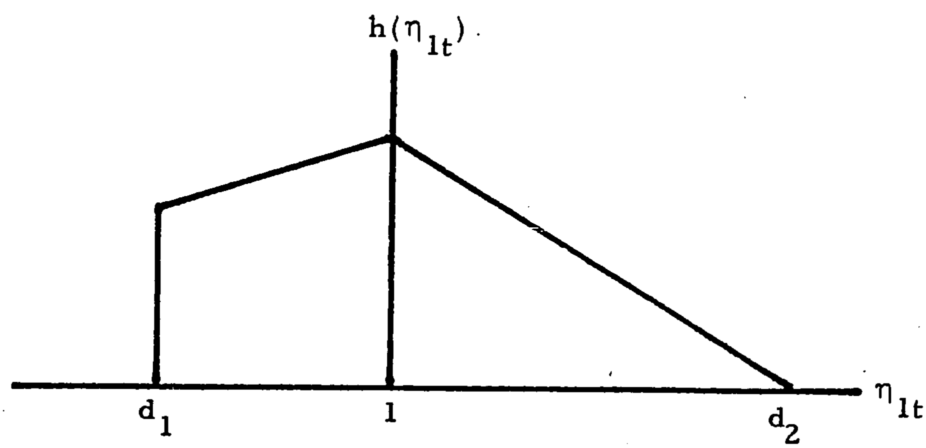

Figure IV-1. Example of a Typical Truncated Triangular Frequency Distribution

To identify a particular program, we will refer to it by the appropriate label in Table IV-1 and include a description of the stochastic conditions that are simulated. Once the type of distribution is specified only the "range parameters" are necessary to completely characterize the frequency function. For example, the label [I-D, Skd. L., (.3, 1.2)] denotes the case I-D where the distribution for the depletion parameter, η_{2t}, is truncated triangular and skewed to the left with η_{2t} ranging between 0.3 and 1.2. All distributions are truncated triangular, unless "U" appears in the description indicating a uniform distribution. Thus, [I-D, Sym. U., (.2, 1.8)] refers to the situation where the distribution for η_{2t} is symmetric and uniform with η_{2t} ranging between 0.2 and 1.8.

A total of 266 programs were considered. For the reader's convenience, a complete list and description of all the programs studied for each of the six specifications of the utility and rent functions appears in Table IV-2. The same set of cases were evaluated for all Classes I - VI of utility and rent functions. Three types of distributions, skewed left, skewed right, and symmetric are included in our analysis. We are interested in determining if the optimal consumption policies are sensitive to the different types of distributions. For each kind of distribution, the programs are arranged in increasing order according to the range of variation for the stochastic parameters. As we will see shortly, this allows us to study the effects of increased uncertainty on resource allocation.

Table IV-2. Program Listings Corresponding to Rent and Utility Specifications I-VI

Stochastic Variation / Distribution	Random Prices η_{1t}, η_{2t} Non Random	Random Depletion Rates η_{1t}, p_t Non Random	Random Growth and Depletion Rates (Complete Dependence) p_t Non Random	Random Growth and Depletion Rates (Complete Independence) p_t Non Random
Uniform Symmetric (Sym. U.)	\$.15×(.8, 1.2) \$.15×(.6, 1.4) \$.15×(.4, 1.6) \$.15×(.2, 1.8)	(.8, 1.2) (.6, 1.4) (.4, 1.6) (.2, 1.8)	(.8, 1.2) (.6, 1.4) (.4, 1.6) (.2, 1.8)	(.8, 1.2) (.6, 1.4 (.4, 1.6) (.2, 1.8)
Symmetric (Sym.)	\$.15×(.8, 1.2) \$.15×(.6, 1.4) \$.15×(.4, 1.6) \$.15×(.2, 1.8)	(.8, 1.2) (.6, 1.4) (.4, 1.6) (.2, 1.8)	(.8, 1.2) (.6, 1.4) (.4, 1.6) (.2, 1.8)	
Skewed Left (Skd. L.)	\$.15×(.6, 1.2) \$.15×(.4, 1.2) \$.15×(.2, 1.2)	(.6, 1.2) (.4, 1.2) (.2, 1.2)	(.6, 1.2) (.4, 1.2) (.2, 1.2)	
Skewed Right (Skd. R.)	\$.15×(.8, 1.5) \$.15×(.8, 1.7) \$.15×(.8, 1.9)	(.8, 1.5) (.8, 1.7) (.8, 1.9)	(.8, 1.5) (.8, 1.7) (.8, 1.9)	

For DG and $\overline{DG}$ conditions, only one range of variation is indicated since we are assuming that η_{1t} and η_{2t} have the same distribution. Recall however, that η_{1t} and η_{2t} are identical for DG, and independently distributed for $\overline{DG}$. For DG programs, only uniform distributions are analyzed. The cost of simulating DG conditions is more than for the other cases because of the computational and memory storage demands on the computer in generating two independently distributed random variables. After reviewing the other cases we did not find that the optimal consumption program for the skewed and symmetric distributions were sufficiently different to warrant including both distributions in the DG programs.

Earlier, we stated that the probability density functions for the stochastic variables in our model, η_{1t}, η_{2t}, and p_t are not known. Except for observations on p_t, there is also no information about the range over which these parameters vary. For the purposes of our study, we assume that each of the parameters varies at its widest limits within a range of 0.2 and 1.8 its expected value. Although the price variation for some programs is greater than the fluctuations in price commonly observed for the yellowfin tuna fishery (see Appendix III-A), these cases are included in our analysis for general interest.

The values for the rest of the parameters in the model are the same as the values used for our analysis of optimal consumption programs for deterministic conditions in the fishery discussed in Chapter III.

Biological Parameters

$a = 3.057$

$b = 1.035 \times 10^{-8}$

$k = 7.85 \times 10^{-5}$

Economic Parameters

$\bar{p} = \mathcal{E}(p) = \$0.15$

$C_1 = 5.0 \times 10^{2}$

$C_2 = 6.0 \times 10^{-2}$

$C_3 = 1.0 \times 10^{5}$

$B = 0.9906$

$G = 4.5 \times 10^{8}$

$\bar{\Delta} = 0.1$

The optimal effort allocations derived with our Markov Decision Process model for each of the programs listed in Tables IV-1 and IV-2 appears in Appendix IV. The results are organized in accord with the program listings and descriptions of Tables IV-1 and IV-2.

Rather than discuss the computational mechanics of our model in the body of this chapter, the interested reader is referred to Appendix III-C for a complete description of the program used to run the Markov model on the Burroughs 6700 computer.

A. 4. Introductory Remarks Concerning the Questions

Having described and identified the set of cases to be examined, we are ready to answer the four questions posed earlier concerning the effect of uncertainty on optimal consumption rules in the fishery. Obviously, it is not our purpose to present an exhaustive study of all possible stochastic environments for the fishery. As a first attempt at solving a difficult stochastic optimization problem--one for which analytical techniques are not available--our objectives are (1) to develop a computational method for selecting optimal decision rules, and (2) to use this method to study an interesting subset of the possible conditions that might prevail in the fishery.

The number of cases we consider is limited by the trade-off between obtaining more information and the additional cost of computer time and analysis required to study each program. As with all computational or simulation models, there is some question as to what extent the results are specific to the model or parameter values assumed. Hopefully, though, the conclusions from our study will help us to formulate general propositions about allocation rules for the fishery. A valuable by-product of our results will be information on other cases that need to be considered. Whenever appropriate, I have indicated additional programs and modifications in the model that might help to extend our results.

Other analysis of optimal consumption and production policies under stochastic conditions have been performed by Leland (1974), Levhari and Srinivasan (1966), Mills (1959), Phelps (1962), and Zabel (1970) and (1971). These studies are not sufficiently similar to our own analysis for a meaningful comparison of results. However, one finding common to all of these studies[3] and applicable to our own model is that optimal rules for allocating resources may be sensitive to the specification of the welfare function and the distribution of the stochastic parameters in the model. Consequently, wherever possible we have tried to indicate which assumptions are critical for certain results in our model to hold.

Before beginning the discussion of Questions 1 - 4 we have two general observations to make on the results we obtained after analyzing all the programs in Table IV-2.

Observation 1: The qualitative nature of our results is the same for all different parameter distributions we employ, whether they be symmetric, uniform symmetric, or skewed.

Although it does not appear that the type of distribution has a significant impact on resource allocation, we will see that the amount of variation in the random parameters has a pronounced effect on optimal decision rules. To be consistent throughout the chapter, in discussing each question we will illustrate our results with examples of optimal programs where the random variables have a uniform symmetric distribution. This is done with the understanding that our observations apply to all the different types of frequency distributions.

Observation 2: Optimal effort allocations corresponding to variable depletion rate cases (specification D) are virtually unaffected by allowing simultaneous variation in the natural growth rate (specification DG and $\overline{DG}$).

Conceivably, for the parameter values of η_{1t} and η_{2t} we analyzed, fluctuations in the depletion rate dominate any effects of growth rate variation. Another explanation might be that random changes in the growth rate have no impact on allocation programs. To test these hypotheses we analyzed programs where only the growth rate was random for each of the six classes, assuming a variation for the parameter η_{1t} of [Sym. U., (.2, 1.8)]. The optimal effort allocations for these programs, listed in Appendix IV, differs only slightly from the deterministic program for each class. This tends to confirm our hypothesis that variations in the growth rate have a negligible effect on allocation programs.

Throughout the rest of this chapter, we will illustrate our results about growth and depletion rate cases with examples of optimal depletion rate programs, D. However, one should understand that these results also apply in equal force to DG and $\overline{DG}$ cases.

B. QUESTION 1

Question 1: How do different attitudes toward social risk bearing as regards variations in resource rents, affect optimal decision rules when uncertainty exists regarding the price of fishery products, the rate of depletion (for a given effort allocation), and the rate of population growth?

To answer Question 1, we contrast optimal decision rules for risk neutral (Class I-III) programs with risk averse (Class IV-VI) policies under identical stochastic conditions, for cases P, D, DG, and $\overline{DG}$. Our results are summarized in Observation 3.

Observation 3: For all variations, P, D, $\overline{DG}$, and DG listed in Table IV-2, a comparison of optimal risk averse programs with risk neutral policies indicates that:

a. At small populations the optimal allocation of effort and the resulting catch for risk averse programs are equal to or larger than the corresponding values for risk neutral policies.

b. At large populations the allocation of effort and the resulting catch for risk averse programs are generally less than the corresponding values for the risk neutral policies.

c. Except for Class III and VI policies, risk averse and risk neutral programs converge toward the same steady state population.

Our observations apply to all variations listed in Table IV-2, although results will be illustrated with certain cases. Sample comparisons between risk neutral and risk averse policies for conditions where price is variable [P, Sym., U., (.6, 1.4)] and where depletion rates are random [D, Sym. U., (.6, 1.4)] appear in Figures IV-2a,b,c and IV-3a,b,c, respectively. Each policy is described by the effort allocation corresponding to population size. In Figures IV-2a,b,c deterministic policies are optimal for the risk neutral social maximizer since price variation doesn't affect resource allocation if the expected price remains unchanged.

B.1. Concavity or Moderation Effect

Parts (a) and (b) of Observation 3 are explained by what we call the "concavity effect." The difference in effort allocation for risk averse and risk neutral policies is schematically represented in Figure IV-4. This difference measures the changes in effort caused by transforming utility from a linear into a concave function of R, or equivalently by changing Class I, II, and III functions to Class IV, V, and VI functions respectively.

In each period, the decision maker selects an allocation of effort based on the trade off between consuming a larger portion of the current stock, but at the expense of reducing the expected future stream of returns from the fishery. Roughly, the optimal policy is to limit current consumption for small stock sizes where the fishing conditions are poor in return for larger expected future revenues from the fishery once the population has increased. Of course for larger populations current consumption increases to take advantage

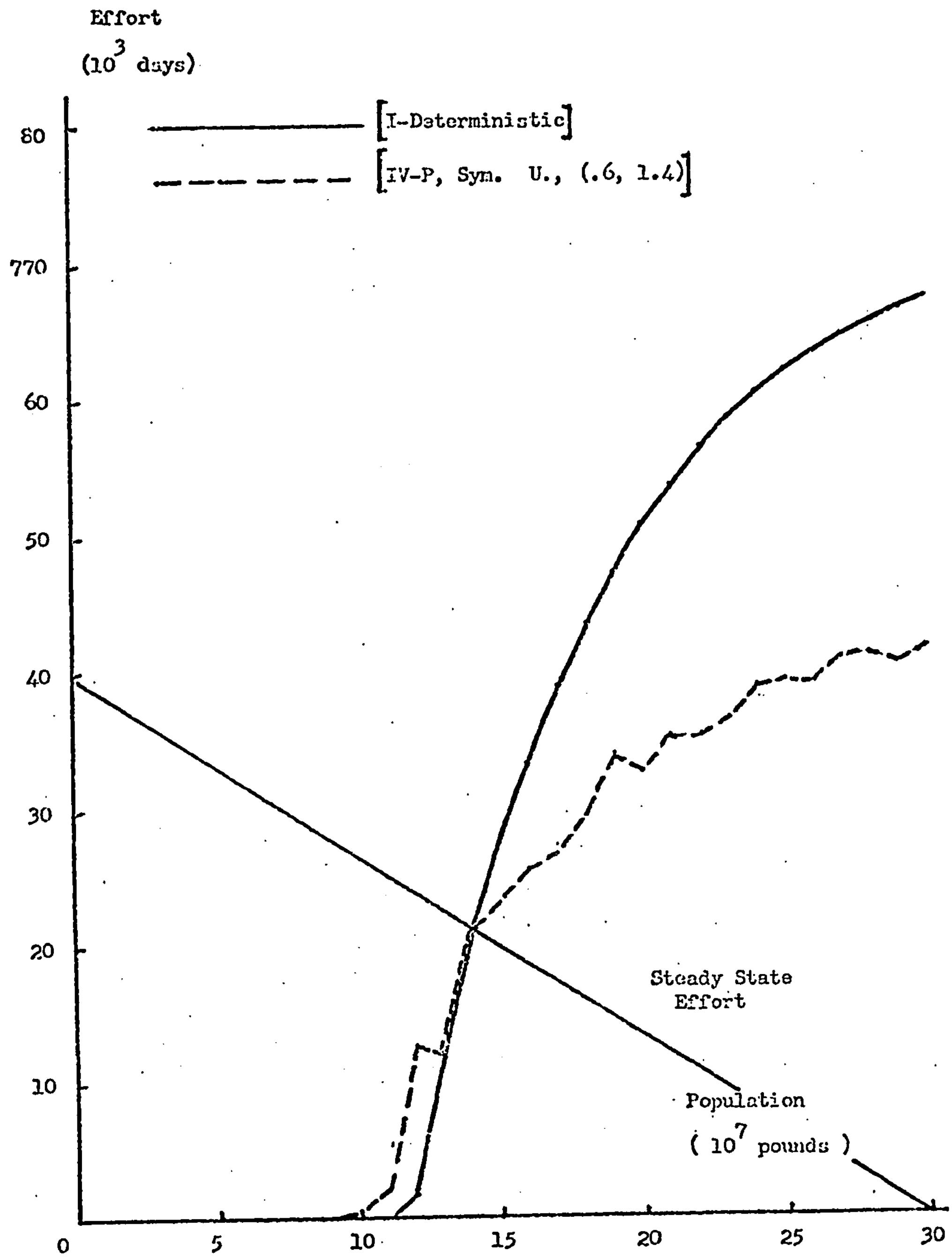

Figure IV-2a. Comparison of Optimal Risk Averse and Risk Neutral Programs with Variable Prices for Classes I and IV

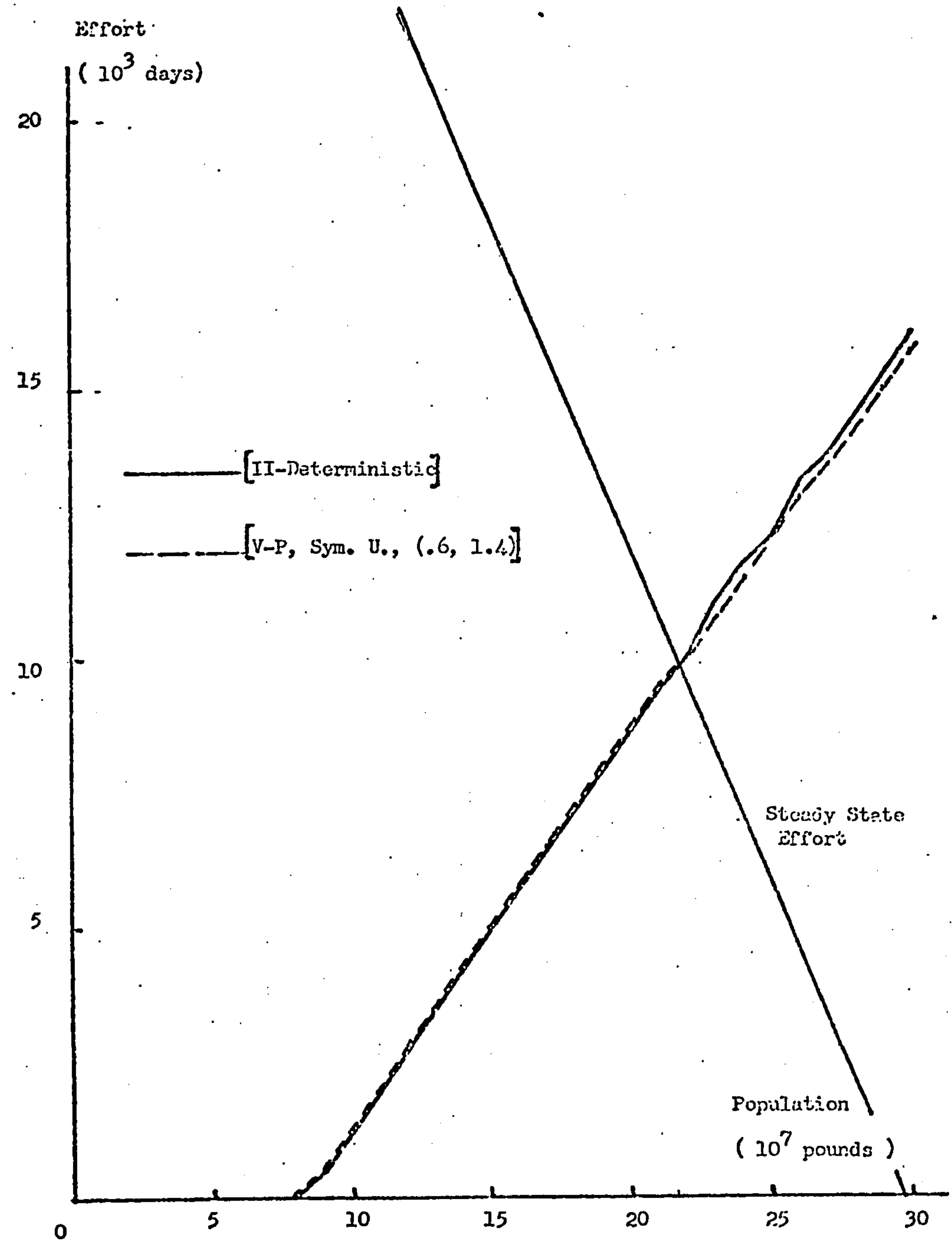

Figure IV-2b. Comparison of Optimal Risk Averse and Risk Neutral Programs with Variable Prices for Classes II and V

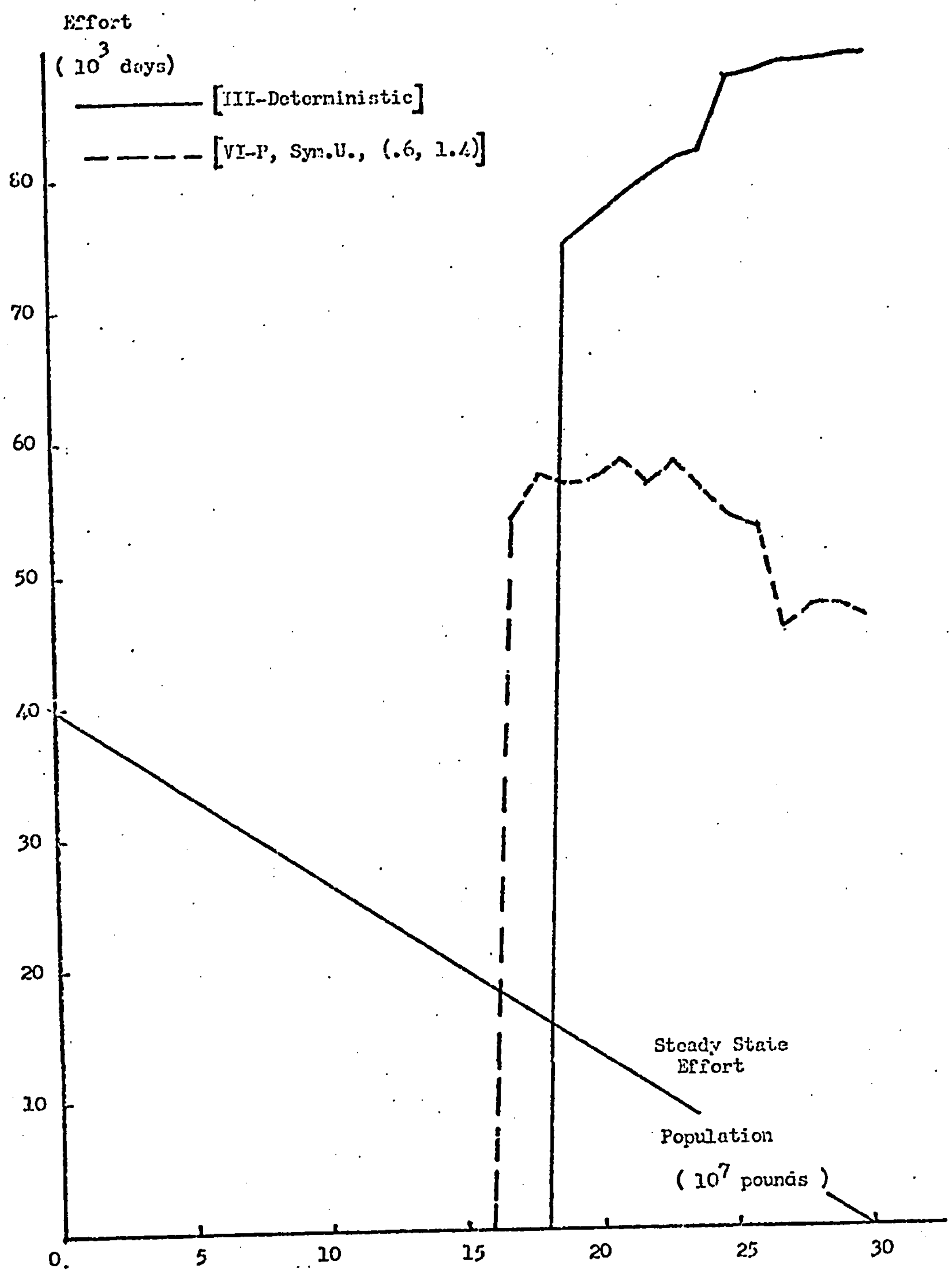

Figure IV-2c. Comparison of Optimal Risk Averse and Risk Neutral Programs with Variable Prices for Classes III and VI

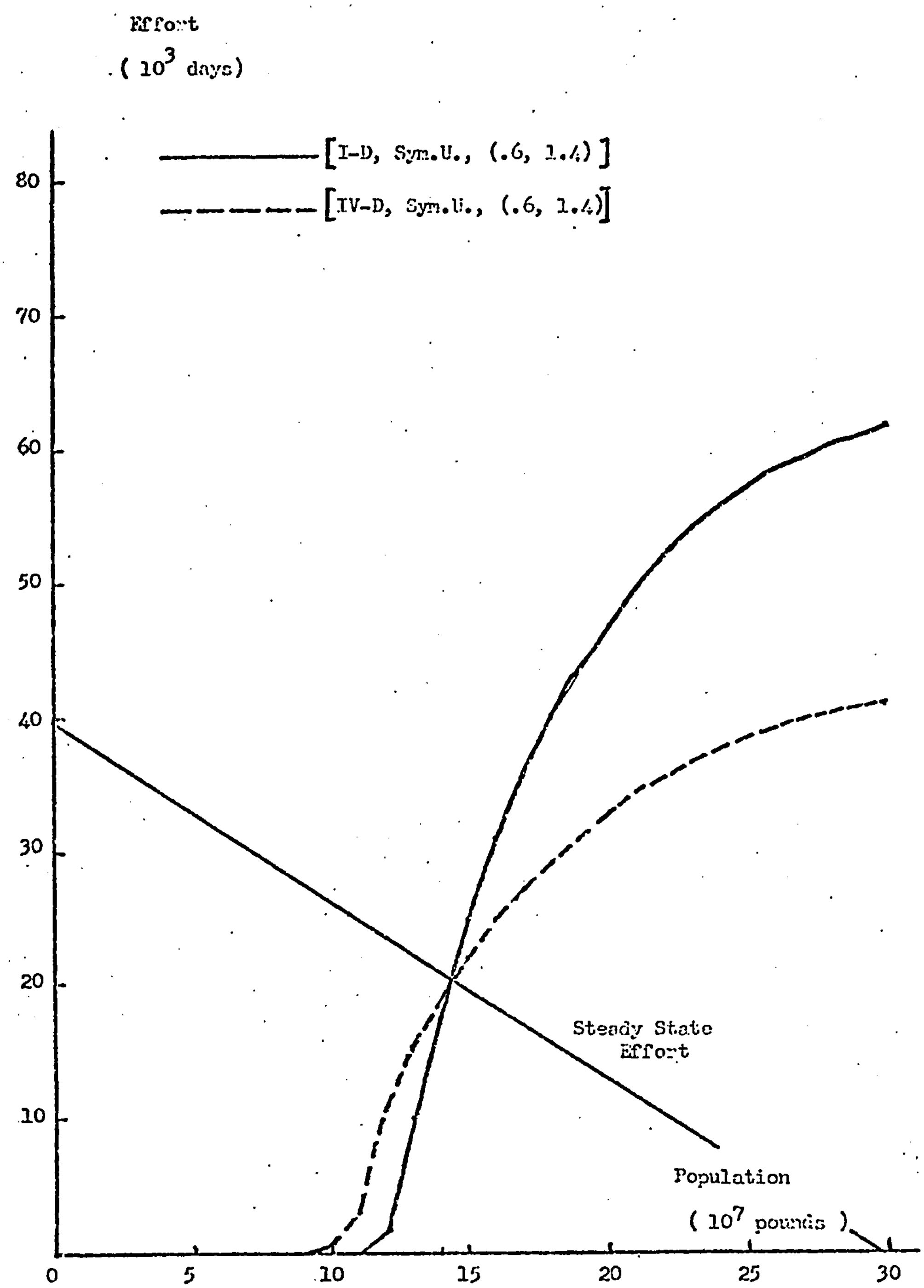

Figure IV-3a. Comparison of Optimal Risk Averse and Risk Neutral Programs with Variable Depletion Rates for Classes I and IV

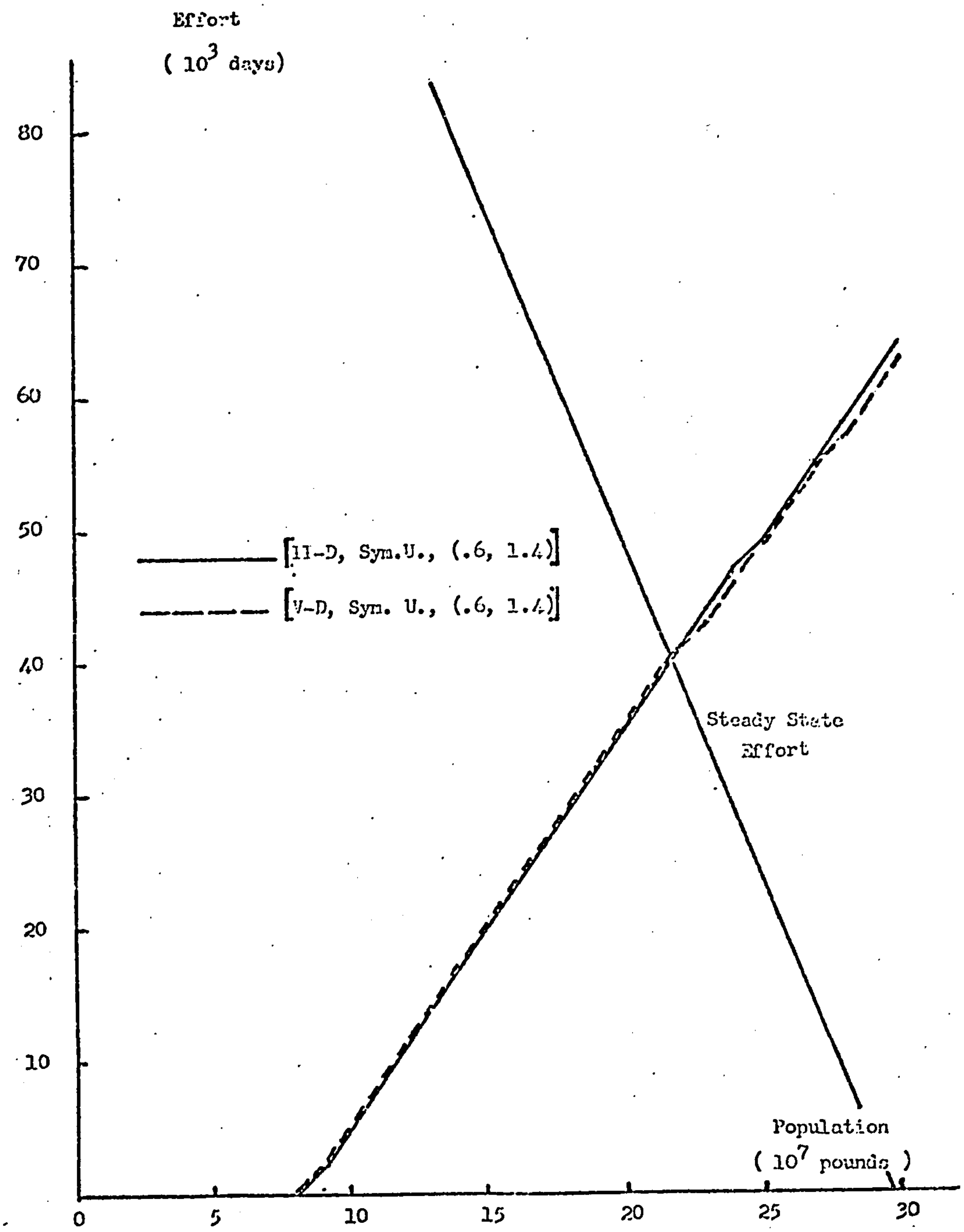

Figure IV-3b. Comparison of Optimal Risk Averse and Risk Neutral Programs with Variable Depletion Rates for Classes II and V

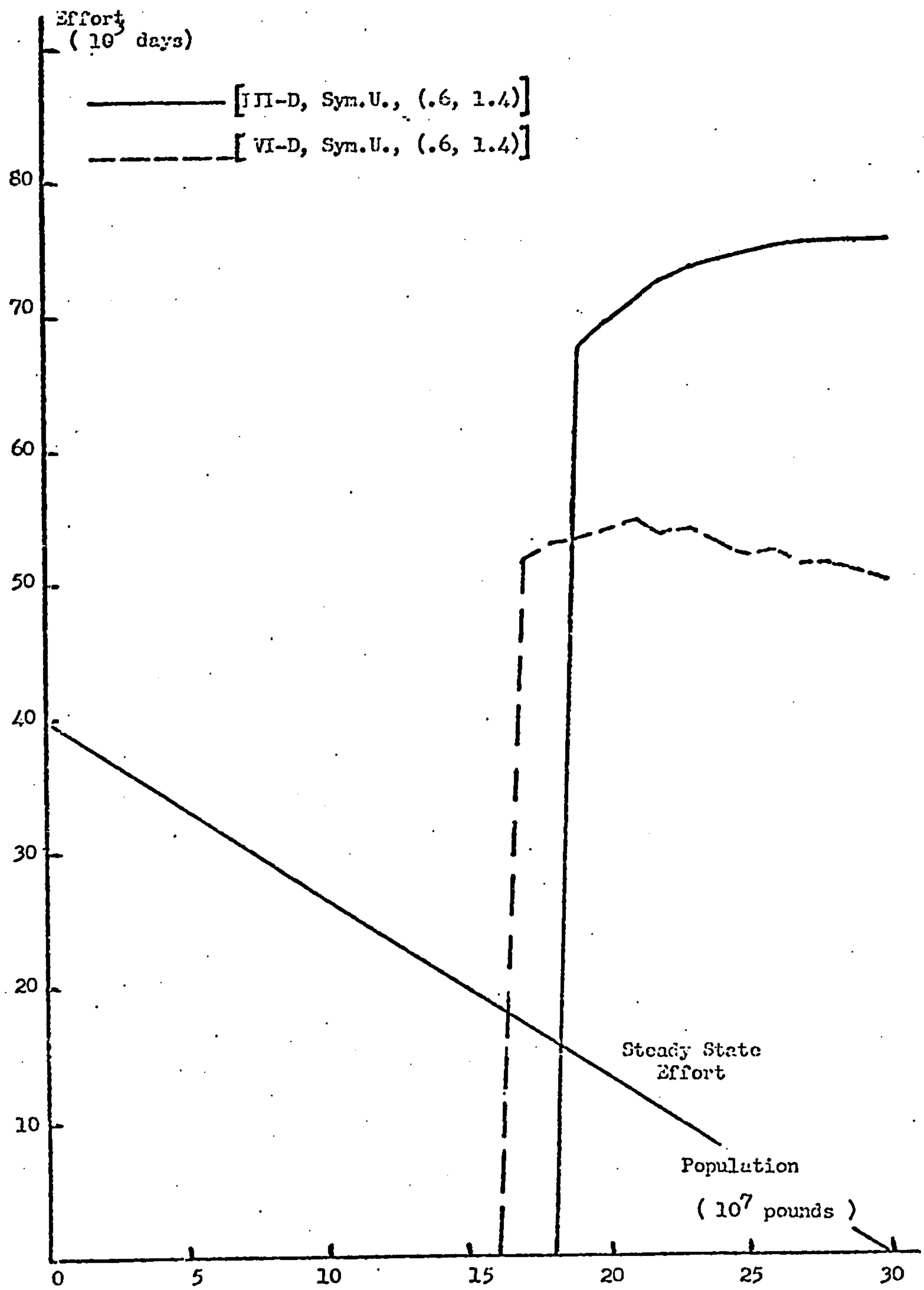

Figure IV-3c. Comparison of Optimal Risk Averse and Risk Neutral Programs with Variable Depletion Rates for Classes III and VI of improved fishing conditions.

Because of decreasing marginal utility, the effect of making utility a concave function of R is to place greater weight on current consumption for small stock sizes where R_t is typically small, and less weight on consumption for larger populations where R_t is greater. This occurs because the addition to utility for a small increase in R_t is greater when returns are small, and vice versa. Another description of this effect, which we shall call the "concavity effect," is that it tends to moderate or smooth out the consumption policy as a function of stock size. That is, the difference in effort allocations and consumption rates corresponding to large and small population sizes is reduced by transforming the utility function. This effect is quite pronounced for Classes I and III as illustrated in Figures IV-2a, IV-2c, IV-3a, and IV-3c.

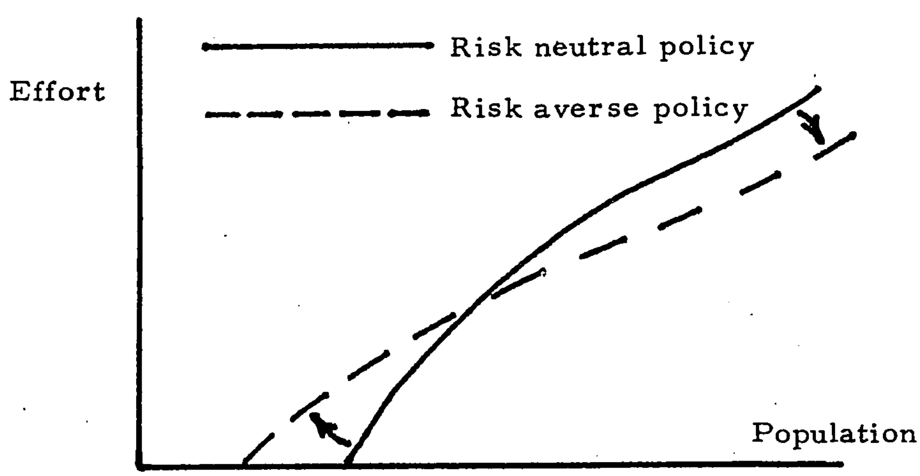

Figure IV-4. Schematic Difference between Risk Neutral and Risk Averse Policies

Notice that R_t is a strictly concave function of E_t for Class II. By arguments similar to those used above, we expect a more moderate consumption policy for II than for the other Classes, I and III. This is verified by examining Figures IV-2a, b, c and IV-3a, b, c. In addition, the concavity effect will be less pronounced for Class II cases since R_t is already strictly concave in E_t.

B.2. Dynamic Properties

In each figure, the points on the line labeled "Steady State Effort" indicate the effort required to maintain the stock at a steady state, assuming population growth and depletion are deterministic.[5] The notion of a steady state becomes obscured under stochastic conditions, when population is perturbed constantly by random variations in growth and depletion rates. However, even in Figures IV-3a, b, c, where depletion rates are random the population tends to increase (decrease) for effort levels lying below (above) the steady state effort line. For example, on average, the population will decrease if the effort allocated exceeds the steady state quantity of effort.

According to Figures IV-2a, b and IV-3a, b, Class (I and IV) and (II and V) programs tend to converge to the same steady state population. Because of the concavity effect, risk averse programs generally converge to equilibrium at a slower rate than risk neutral policies. This suggests a generalization of the result derived in

Appendix III-D. Recall that for deterministic conditions, if the optimal program corresponding to a specific objective function converges to a particular steady state, then the optimal program for any positive concave transformation of the original objective function converges to the same steady state. Our observations suggests that the result might also hold under stochastic conditions.

For Class III and VI programs, as depicted in Figures IV-2c and IV-3c, "cyclical" as opposed to "steady state" fishing is optimal. The cycles are less pronounced for risk averse policies than for risk neutral programs due to the concavity effect.

C. QUESTION 2

Question 2: What is the effect on optimal consumption strategies for increased uncertainty regarding prices, and depletion and growth rates?

To answer this question we analyze changes in consumption policies for different distributions of prices, and growth and depletion rates. All these distributions belong to the class of mean-preserving spreads (the mean of the random variable is unchanged for all distributions), and are ordered according to how "risky" or "uncertain" they are. Adopting the definition of "increasing uncertainty" from Hadar and Russell (1969), Hanoch and Levy (1969), and Rothschild and Stiglitz (1970), we say that one distribution, f, is more uncertain than another, g, if

$$\int U(x)\, f(x)\, dx \leq \int U(x)\, g(x)\, dx \qquad (3)$$

for all risk averters--those with concave utility functions, U. It can be shown[6] that (3) is formally equivalent to

$$T(Y) = \int_a^b (F(x) - G(x))\, dx, \;\; T(Y) \geq 0 \;\text{ and }\; T(b) = 0 \qquad (4)$$

where F and G are the cumulative density functions corresponding to f and g, and it is assumed that the points of increase for F and G are contained in the closed interval $[a, b]$.

Looking at Table IV-2 the distributions, symmetric uniform, symmetric, skewed right, and skewed left for each of the random parameters, p_t, η_{1t}, and η_{2t} are arranged according to the length of the interval over which the variable is allowed to range. It is easy to verify that according to condition (4) the distributions become more risky or uncertain as the range of variation for each of the parameters increase. For example, the distribution of price is more uncertain for [Sym. U., (.4, 1.6)] than it is for [Sym. U., (.6, 1.4)], and [Skd. L., (.4, 1.2)] is more uncertain than [Skd. L., (.6, 1.2)]. These distributions and their corresponding cumulative density functions are represented in Figures IV-5a and IV-5b. In each case the distribution with the wider range is more risky by the conditions stated in (4).

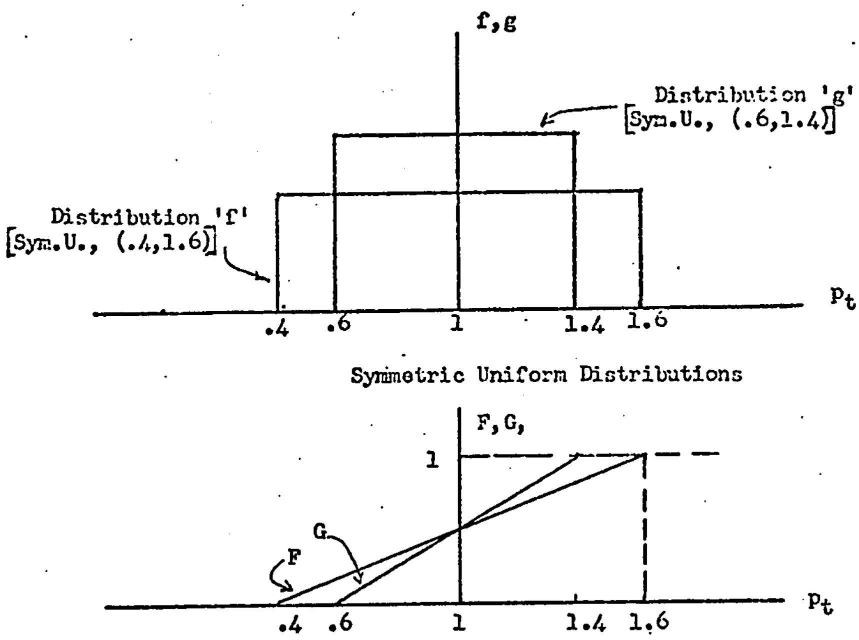

Figure IV-5a. Mean Preserving Distributions - Symmetric Uniform

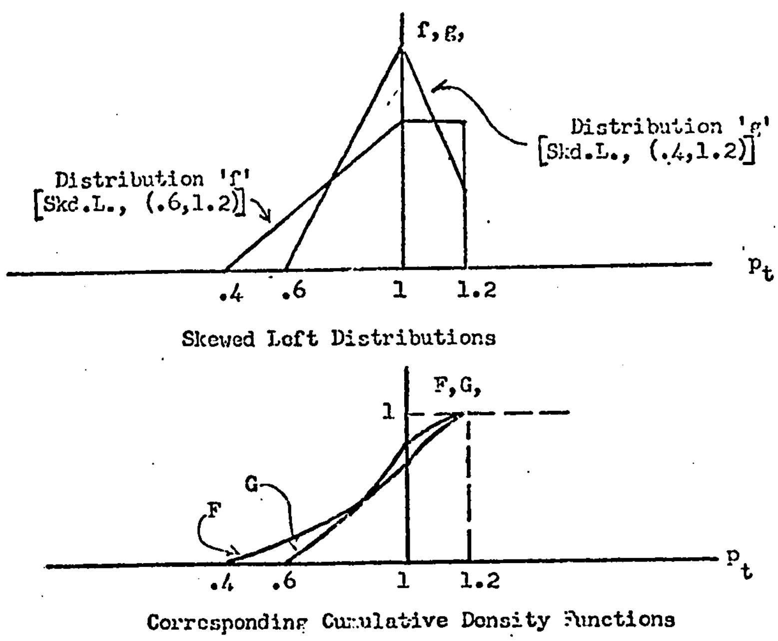

Figure IV-5b. Mean Preserving Distributions - Skewed Left

The social attitudes for risk bearing are important in assessing the impact on optimal allocation programs of increasing uncertainty regarding the key parameters in our model. To sharpen our analysis we consider the effect of increasing uncertainty in two sections--the first dealing with risk neutral social planners, and the second dealing with risk averse social maximizers. Within each section effects of increased variations in prices, and increased uncertainty regarding depletion and growth rates are analyzed separately.

From the results obtained here we can also compare resource use under deterministic conditions with resource allocation in a stochastic environment where uncertainty exists about prices, and growth and depletion rates.

C. 1. Increased Variations in Price--Risk Neutral Social Planner

Variations in price have no effect on resource allocation for the risk neutral social maximizer as long as the expected price remains unchanged.

C.2. Increased Variations in Growth and Depletion Rates--Risk Neutral Social Planner

Changes in resource allocation for Classes I - III caused by increased uncertainty in growth and depletion rates are analyzed for all the cases of variations listed in Table IV-2 for D, DG, and $\overline{DG}$.

Observation 4: For the risk neutral maximizer the effect of increased variation in growth and depletion rates is characterized by the following comments:

a) Increasing variation in growth and depletion rates tend to decrease the optimal allocation of effort and the resultant catch corresponding to each population size.

b) This dampening effect on effort is greatest for Classes I and III rent functions. Within each class, the effect is more pronounced at the high end of the population scale where catches are typically large.

The effect of increasing uncertainty in the depletion rate on optimal programs for Classes I - III is represented in Figures IV-6a, b, c.

Comparing the small variation cases [Sym. U., (.6, 1.4)] with the large variation situations [Sym. U., (.2, 1.8)] the change in effort increases with greater absolute variation in catch. This variation is proportional to the expected catch L, since $L_t = \eta_{2t} kX_t E_t = \eta_{2t} \bar{L}$.

As noted in Observation 4, and looking at Figures IV-6a, b, c we find that (1) the greatest effort adjustment occurs for Classes I and III programs, and (2) within each class, changes in effort increase with population size. Note that the expected value and variation in catch is large for each of these situations. Generally L increases with population, and compared to Class II programs, the expected catch and the variation in L_t are greater for Classes I and III policies particularly at the upper end of the population scale.

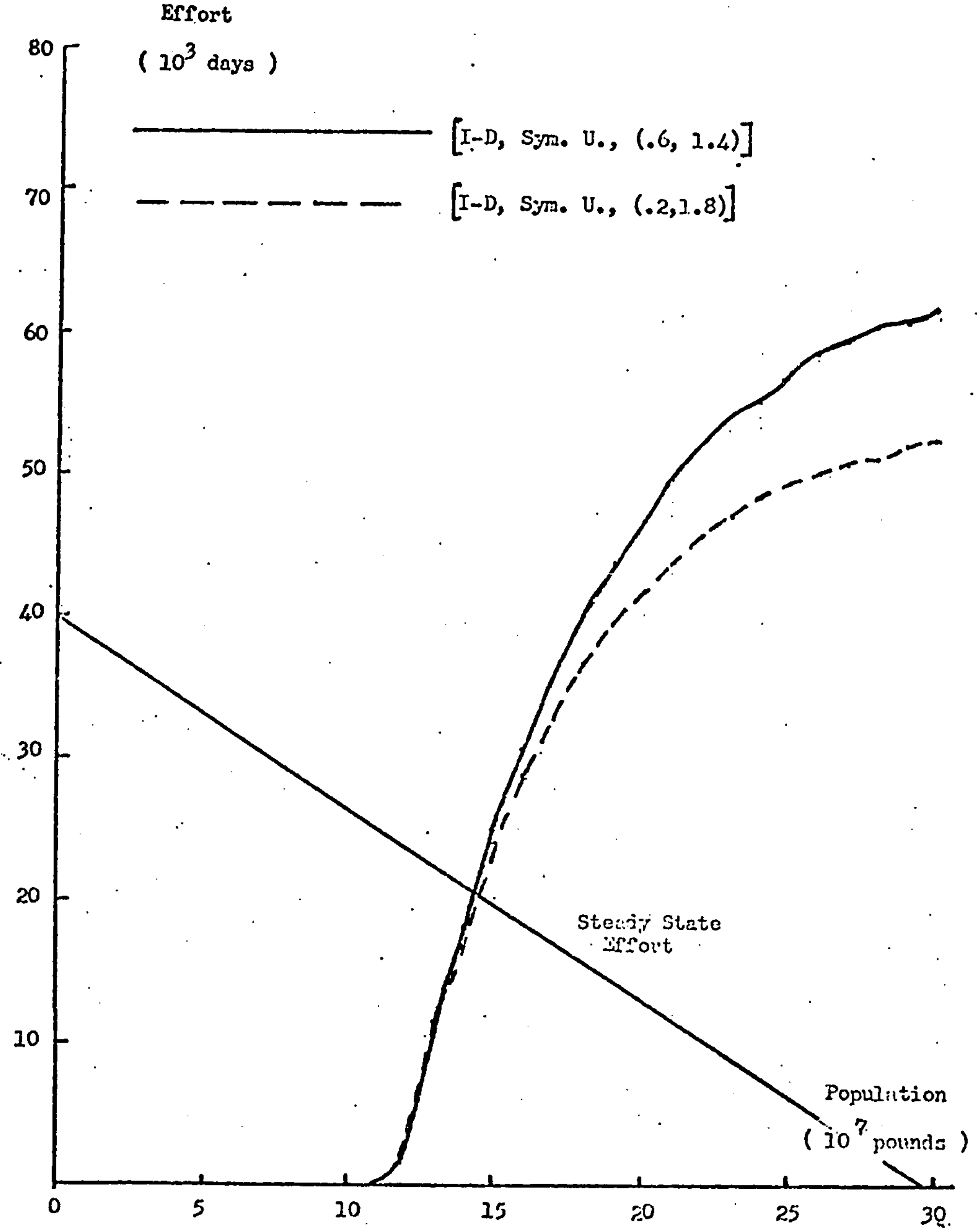

Figure IV-6a. Comparison of Optimal Stochastic Programs with Increasing Variation in the Depletion Rate for Class I

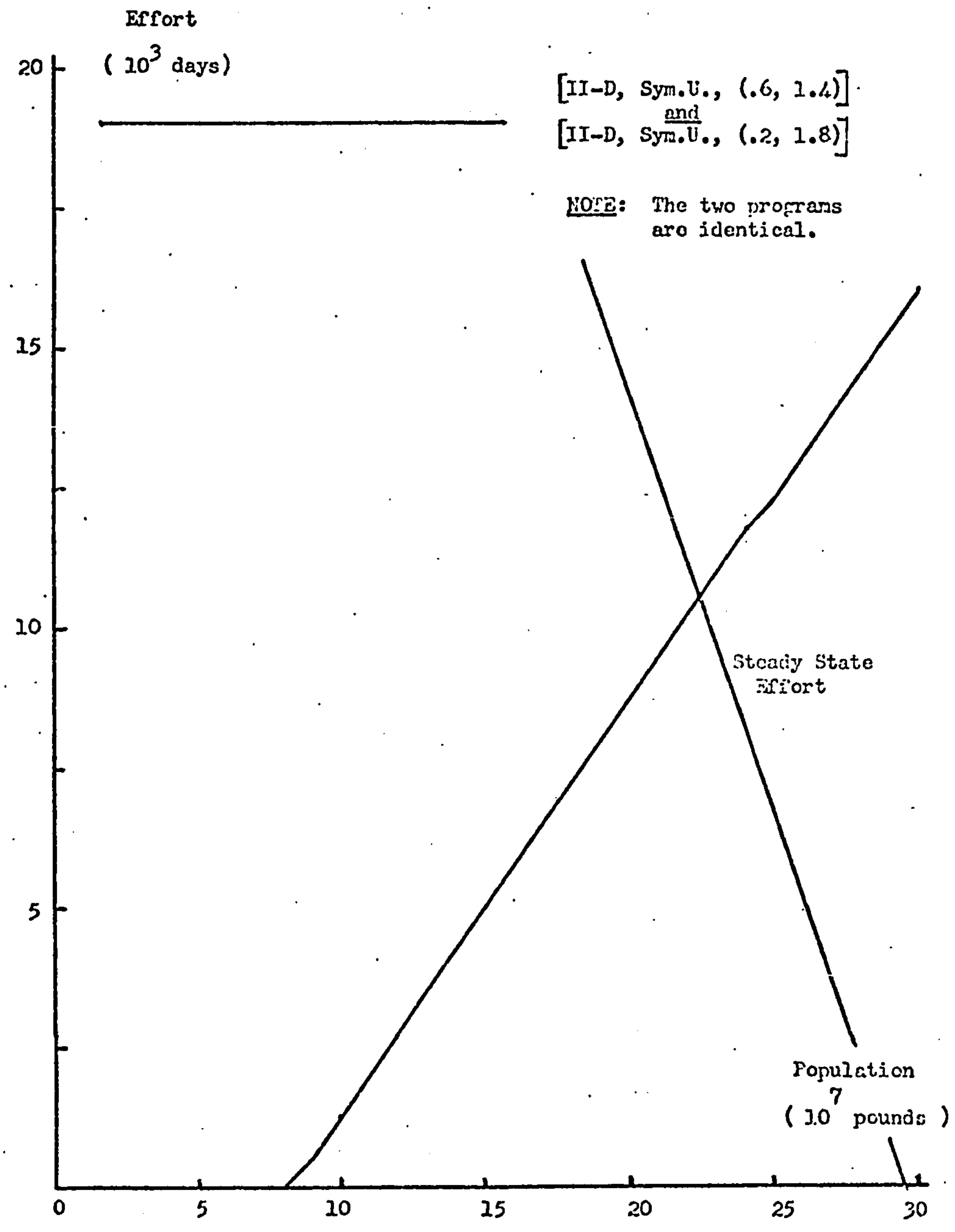

Figure IV-6b. Comparison of Optimal Stochastic Programs with Increasing Variation in the Depletion Rate for Class II

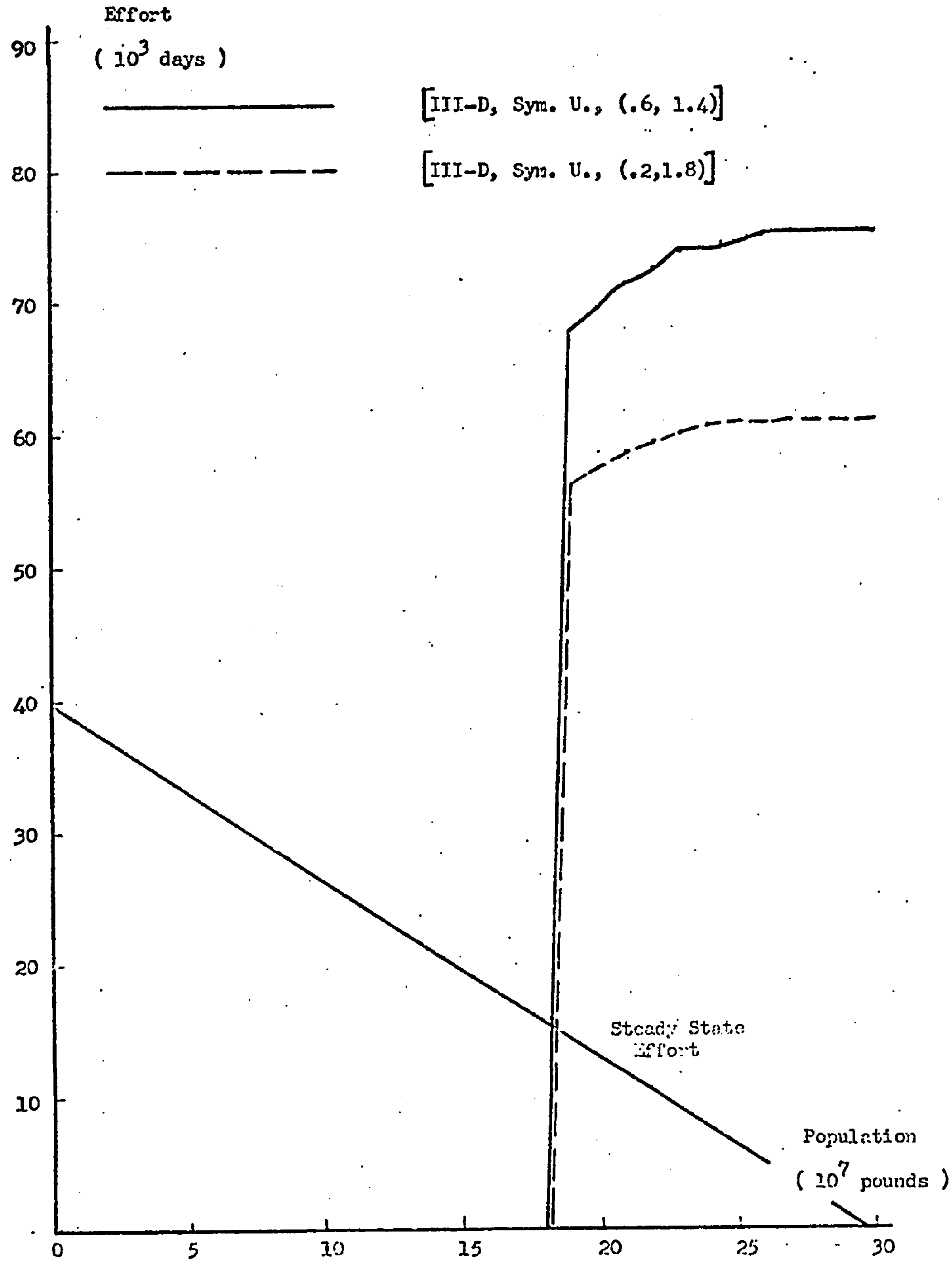

Figure IV-6c. Comparison of Optimal Stochastic Programs with Increasing Variation in the Depletion Rate for Class III

C.3. Increased Variation in Prices, Growth and Depletion Rates--Risk Averse Social Planner

The effect of increasing variation in prices, growth and depletion rates on Class IV - VI programs are analyzed for all the P, D, $\overline{DG}$, and DG variations listed in Table IV-2.

Observation 5:

a. With increasing variation in prices or growth and depletion rates, the allocation of effort and resultant expected catch for small (large) populations are the same or increasing (decreasing) for Classes IV and V.

b. With increasing variation, the allocation of effort is generally decreasing and more evenly distributed over population states for Class VI.

c. The greatest change in effort caused by increasing uncertainty in prices or growth and depletion rates occurs for Classes IV and VI.

Changes in optimal programs for Classes IV - VI caused by increasing variation in prices and depletion rates are presented in Figures IV-7a, b, c and Figures IV-8a, b, c, respectively. A plausible explanation for our findings in Observation 5 is that the dispersion in rents, R_t, is proportional to the size of the catch when either p_t or η_{2t} are random. For all programs the optimal catch generally increases with population. Since the decision maker is averse to variations in R_t he tends to increase his catch for small populations, despite poor fishing conditions, since the dispersion in returns is

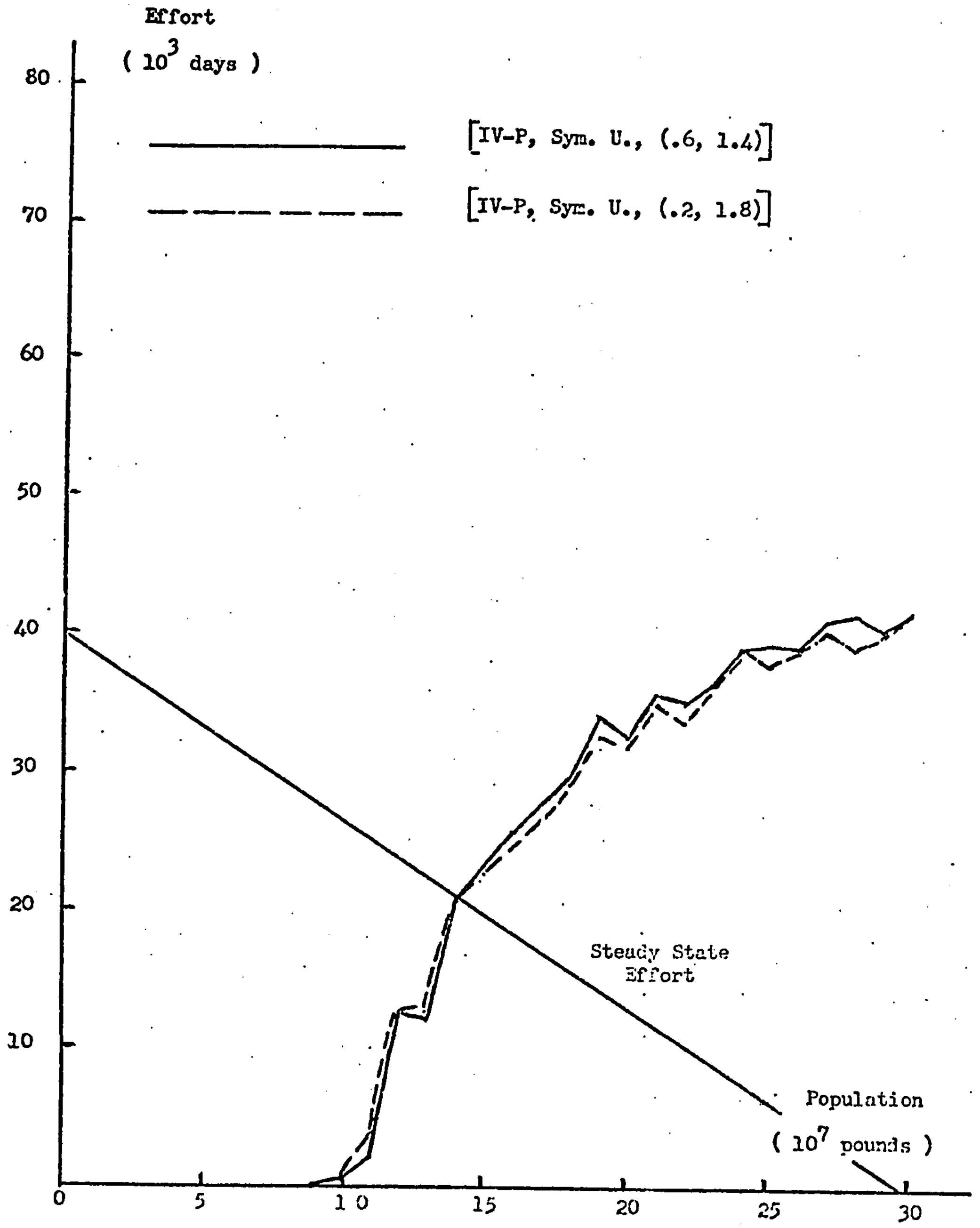

Figure IV-7a. Comparison of Optimal Stochastic Programs with Increasing Variation in Price for Class IV

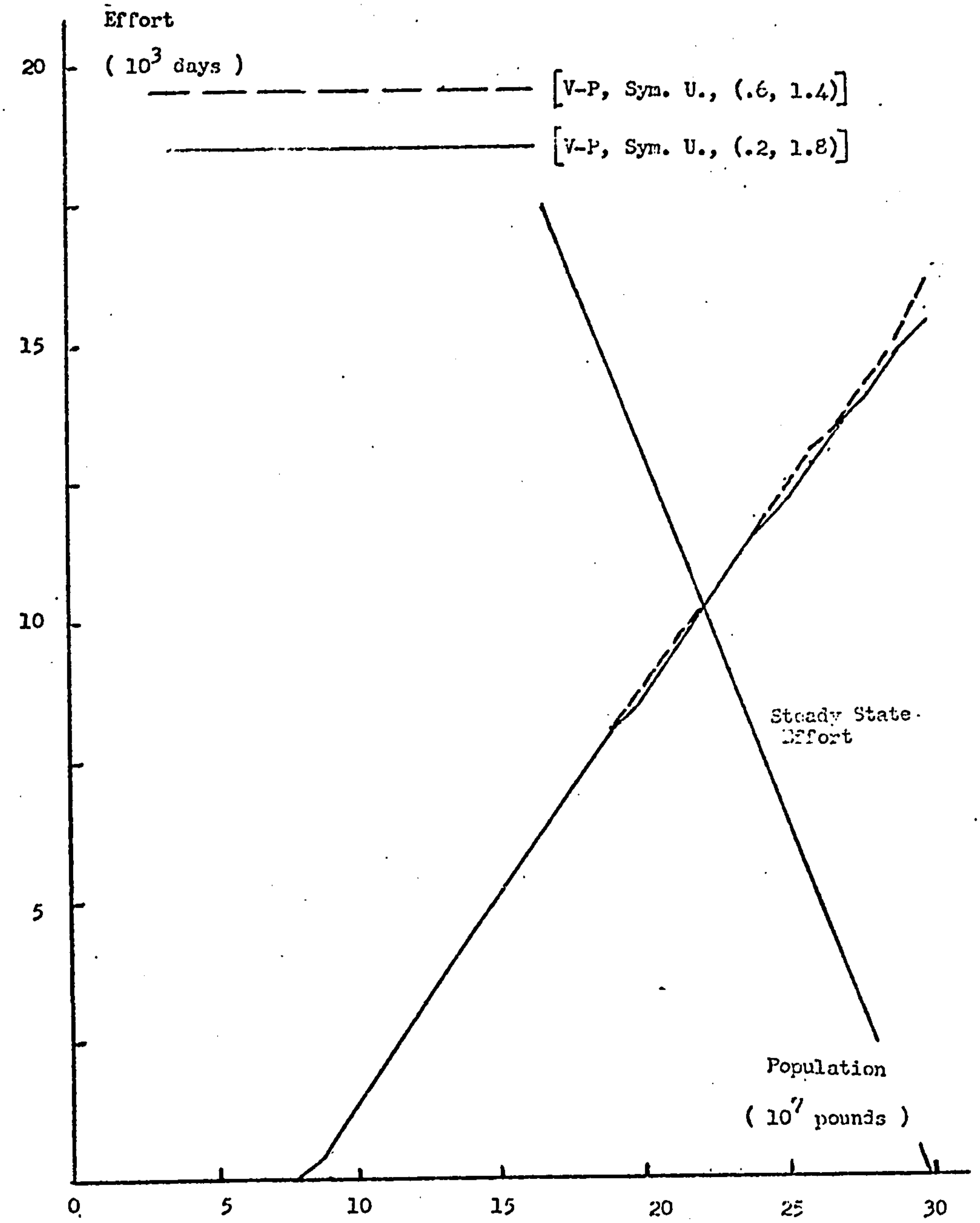

Figure IV-7b. Comparison of Optimal Stochastic Programs with Increasing Variation in Price for Class V

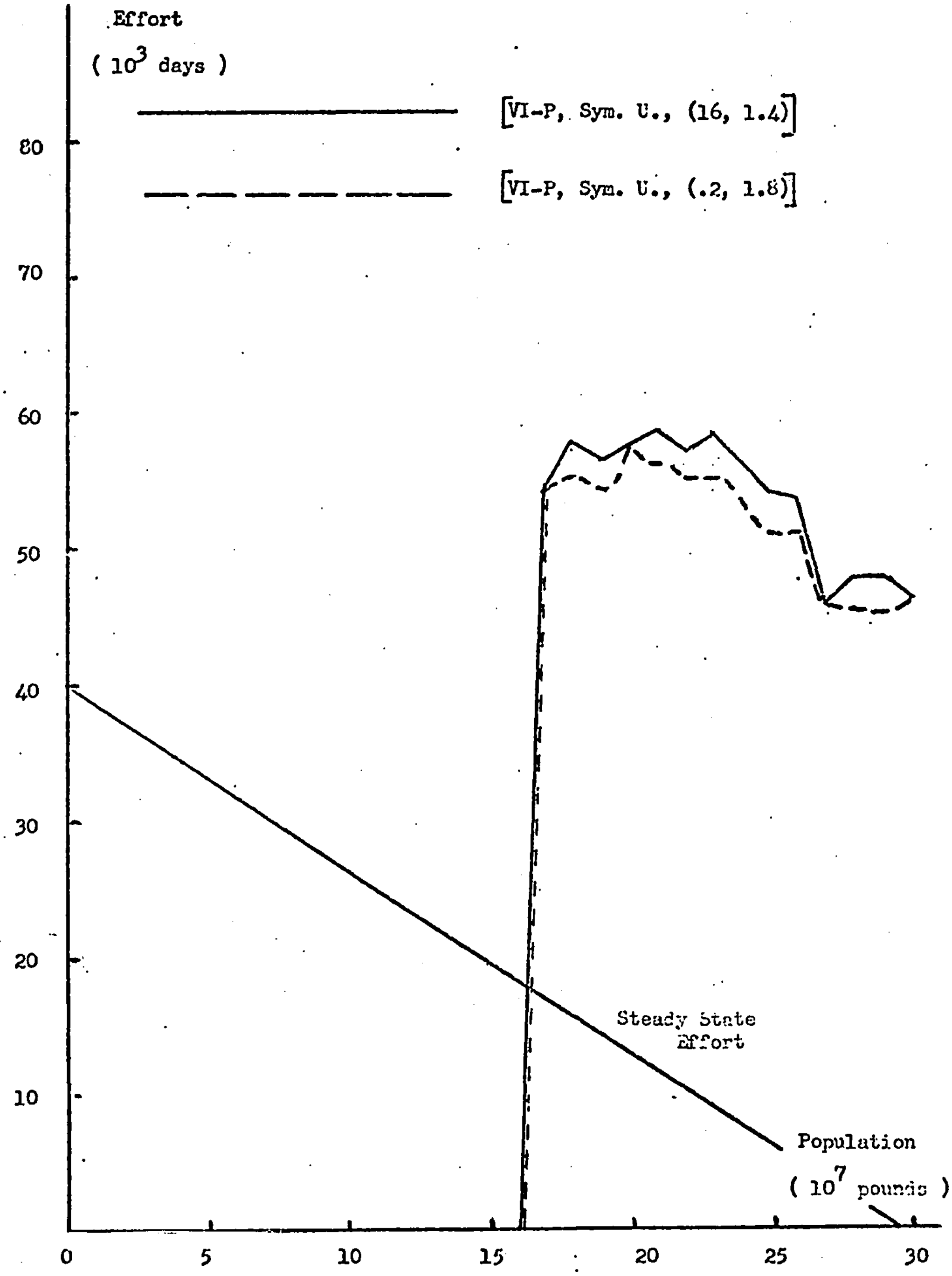

Figure IV-7c. Comparison of Optimal Stochastic Programs with Increasing Variation in Price for Class VI

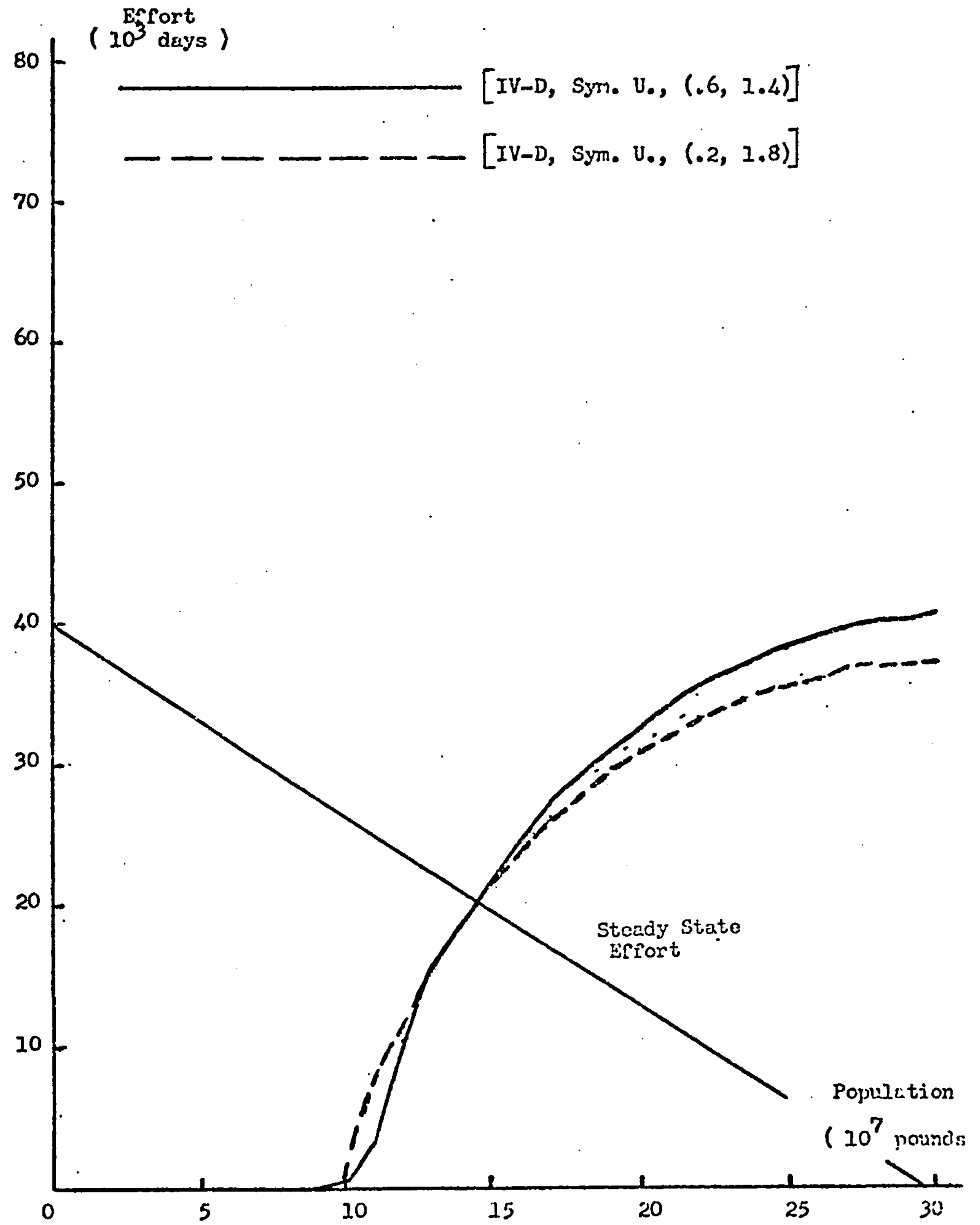

Figure IV-8a. Comparison of Optimal Stochastic Programs with Increasing Variation in the Depletion Rate for Class IV

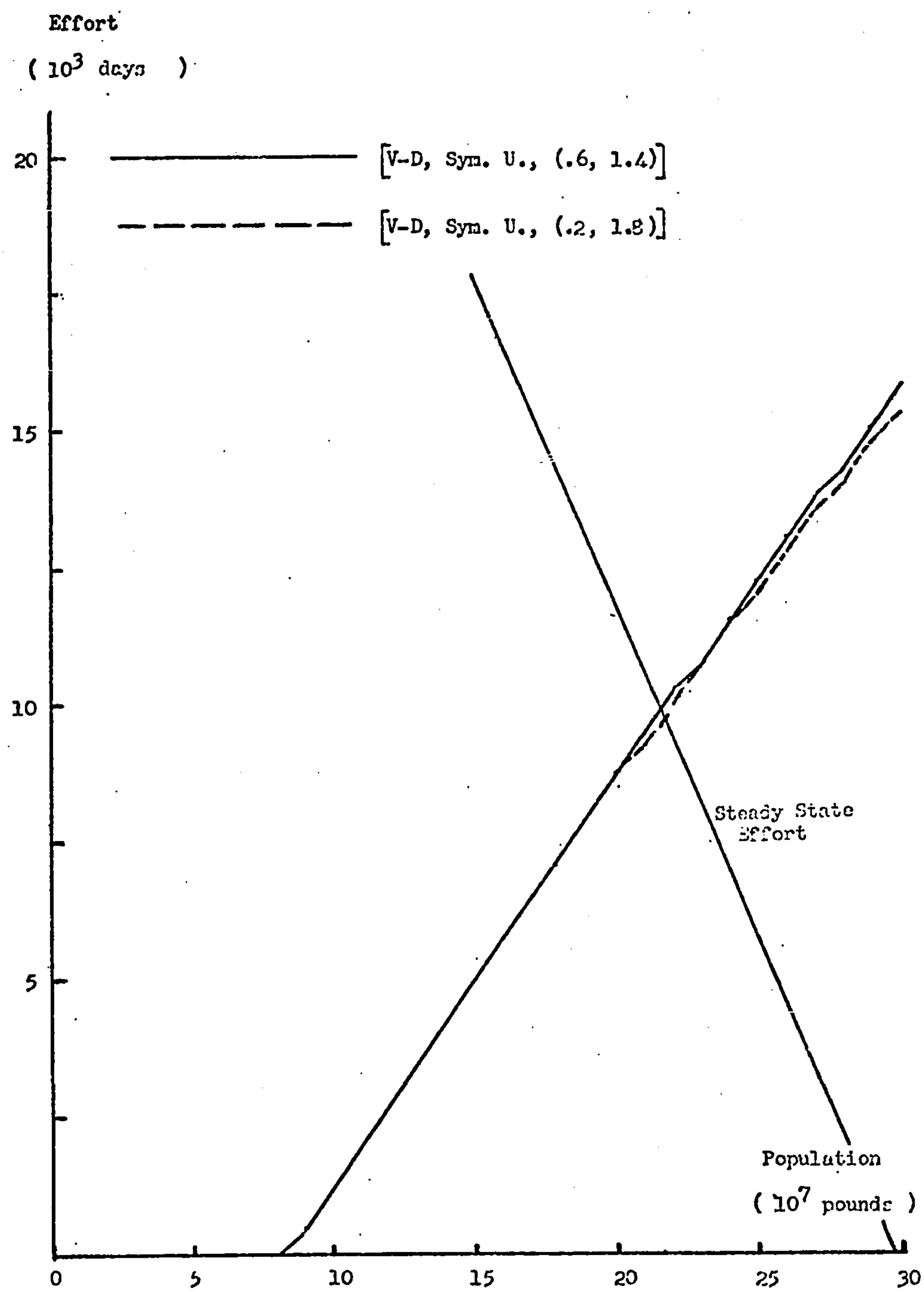

Figure IV-8b. Comparison of Optimal Stochastic Programs with Increasing Variation in the Depletion Rate for Class V

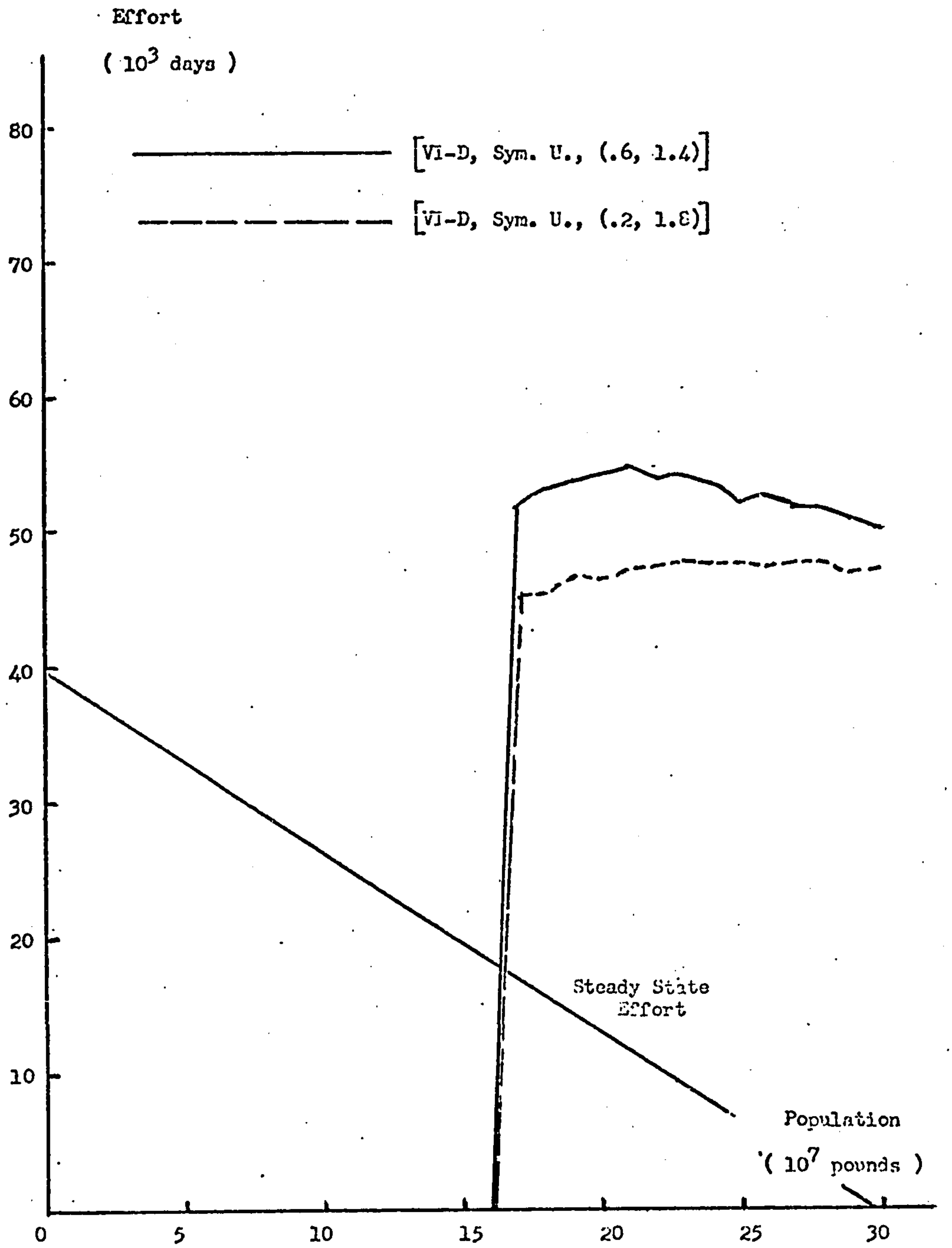

Figure IV-8c. Comparison of Optimal Stochastic Programs with Increasing Variation in the Depletion Rate for Class VI smaller, and to decrease his catch at larger populations, because of the greater dispersion in returns.[7] A simple method to verify this hypothesis, which we save for a later study, would be to analyze the effect on consumption programs of variations in returns that are independent of the size of the catch. Examples of these are fluctuations in repair and maintenance costs for breakdowns in radar and navigational equipment on fishing vessels, which presumably occur at random points in time.

Effort allocations are distributed more evenly over population sizes for Classes II and V than for the other classes, due to the concavity of the rent function. Consequently, variations in the depletion rate, which tend to even out effort allocations, have less of an impact on Class V optimal programs.

D. QUESTION 3

Question 3: Is it possible to account for the social attitudes towards risk bearing in the social discount rate?

This question is not to be confused with the issue of whether or not private costs of risk bearing represent social costs as well, and should therefore be taken into account in judging the desirability of public projects. Rather, our concern is with evaluating different analytical methods for representing risk aversion, assuming that the variability in fishery rents is a social cost that effects resource allocation decisions.

An alternative to capturing attitudes for risk bearing in the form of the utility function, is to employ a "risk adjusted" interest rate for discounting future uncertain returns. In this case the optimal consumption strategy is determined by choosing effort in each period to maximize the present value of fishery rents,

$$\sum_{t=0}^{\infty} B' \mathcal{E}[R(X_t, E_t)\bar{\Delta}]; \quad B' = \frac{1}{1+\rho'} \tag{5}$$

where the rate of discount ρ' includes a "risk premium" yield over and above the "riskless" rate of interest ρ.

In the literature on cost-benefit analysis, by far the most common method of adjusting for risk is through the discount rate. Proponents of this procedure argue that the alternative of representing risk preferences with different forms of the utility functions requires direct knowledge of consumer's utility functions, and is therefore more difficult to implement.[8] However, the simplicity of the present value criteria in equation (5) is deceptive. In practice it is not easy to determine the correct value of ρ'. Several methods for calculating the social discount rate have been proposed, but all of them are difficult to implement.[9] However, a more serious objection to employing risk adjusted discounting is that risk is not a simple compounding function of time.[10] For example, in our model, variations in rent are independent of time and correspond to the size of the expected catch when there is uncertainty about prices or the rate of depletion. Our general conclusion, stated formally in Observation 6 is that programs for exploitation of the fishery that are derived from maximizing the risk adjusted present value of returns, appearing in equation (5) are non optimal.

Observation 6: For each type of variation in our model, P, D, $\overline{DG}$, and DG, there does not exist a B' such that the solution to the problem

$$\max_{E_t} \sum_{t=0}^{\infty} B'^t \, \mathcal{E}[R(X_t, E_t)\bar{\Delta}]$$

$$\text{subject to } X_{t+1} = X_t + [\eta_{1t}(a - bX_t)X_t - \eta_{2t}kX_tE_t]\,\bar{\Delta} \tag{6a}$$

yields a set of E_t's which are optimal for the problem

$$\max_{E_t} \sum_{t=0}^{\infty} B^t \, \mathcal{E}[U(R(X_t, E_t))]\,\bar{\Delta}$$

where $U(R(X_t, E_t)) = \ln(G + R(X_t, E_t))$. It is convenient to organize our discussion of Observation 6 into two sections; one dealing with optimal programs for price uncertainty, the other with optimal strategies for growth and depletion rate variation.

D. 1. Risk Adjusted Discounting for Variable Price Programs

As a general result, we found that the effect of increasing the social discount rate ρ (equivalent to decreasing the discount factor, B), for all programs, regardless of the type of utility function or parameter variations involved, was to encourage a higher level of current consumption of the fishery resource. This is apparent for example in a comparison of optimal effort allocations corresponding to different discount rates for Class I - III deterministic programs appearing in Figures IV-9a, b, c. Intuitively, it seems natural for society to consume a larger portion of the resource currently as future felicities become less important.

Turning now to specific cases, what can we infer about the effect of increasing price uncertainty on optimal consumption programs? If the social aversion to variations in returns is represented analytically in higher discount rates, then current consumption at all population levels tends to increase as price becomes more uncertain as we see from Figures IV-9a, b, c. This is contrasted with the alternative convention of representing risk preferences in the form of the utility function. In this case current consumption increases at small populations and decreases for large populations as price variation increases. This disparity is not surprising since the adjusted discounting procedure treats risk as a simple compounding function of time, even though the variations in rent are proportional to the catch and independent of time.

D.2. Risk Adjusted Discounting for Variable Depletion and Growth Rate Programs

The same conclusion we reached above, that risk adjustment via the discount rate causes distortions in optimal resource allocation,

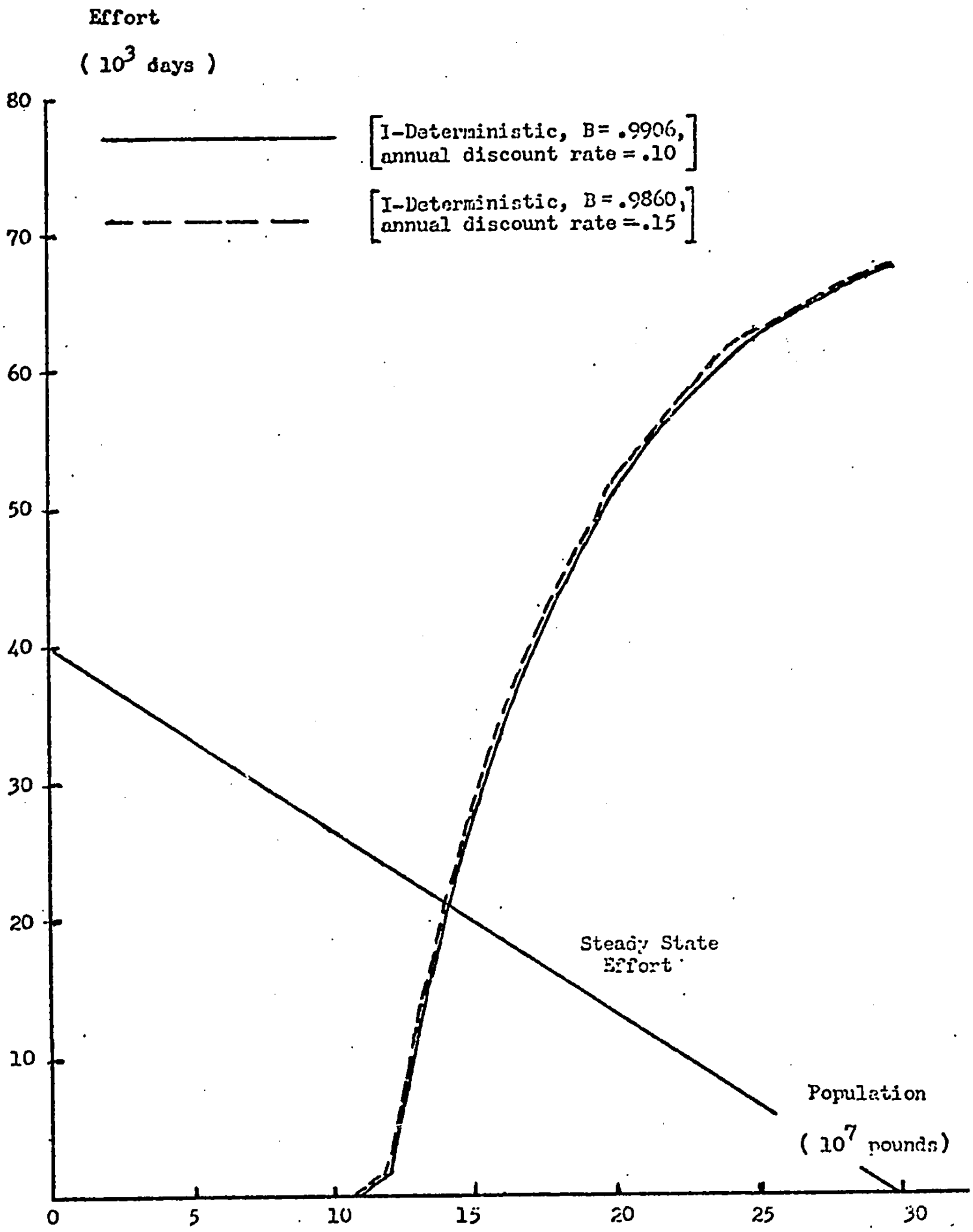

Figure IV-9a. Comparison of Optimal Deterministic Programs with Annual Discount Rates of 10% and 15% for Class I

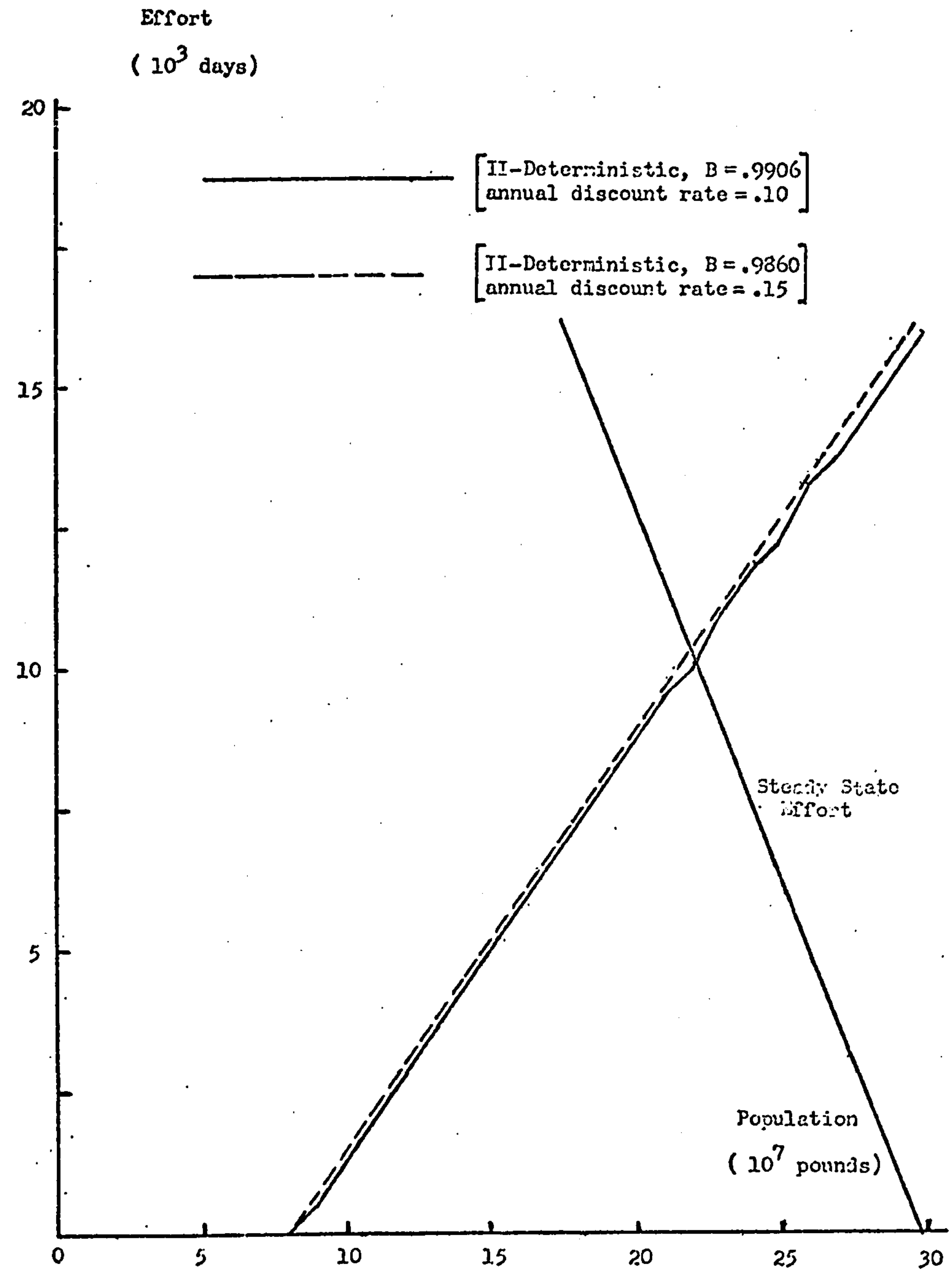

Figure IV-9b. Comparison of Optimal Deterministic Programs with Annual Discount Rates of 10% and 15% for Class II

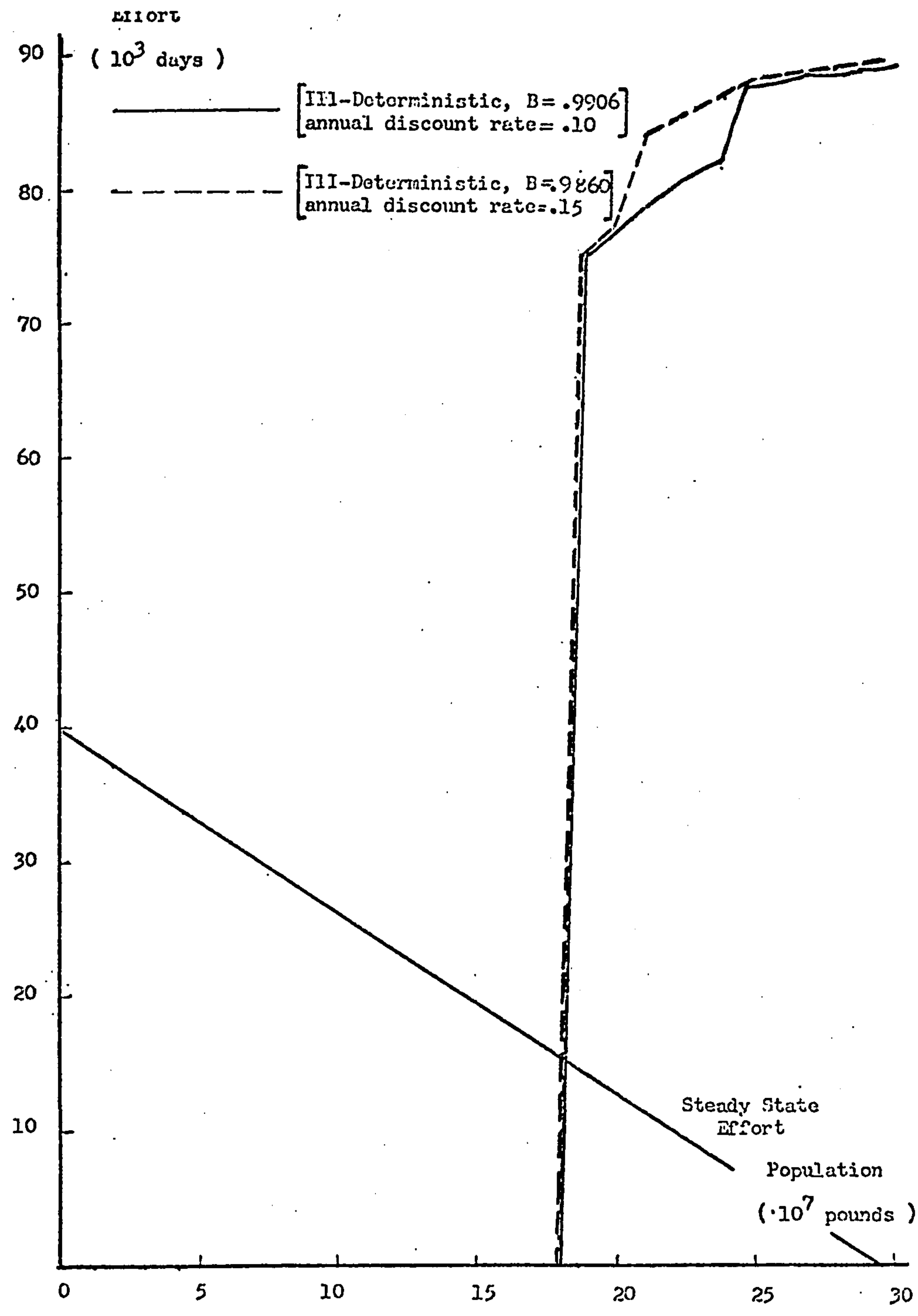

Figure IV-9c. Comparison of Optimal Deterministic Programs with Annual Discount Rates of 10% and 15% for Class III applies here as well. This is illustrated by the examples appearing in Figures IV-10a, b, c, where the optimal programs derived by maximizing the two different welfare functionals in (6a) and (6b) are compared for the variable depletion rate case [Sym. U., (.6, 1.4)]. The arrows in each figure indicate that with the risk adjusted discounting model, the effort allocation increases as the discount rate is adjusted upward to account for risk aversion. As before in the price variation case, there is no single overall adjustment in the interest rate that can serve as a consistent and accurate measure of the riskiness in fishery returns.

D.3. Another Approach to Risk Adjustment Through the Discount Rate

Using a different procedure, Leland[11] (1974) has shown that under special circumstances the solution to a certainty problem, where the discount rate ρ is adjusted to ρ' for risk, will coincide to the optimal solution for a corresponding stochastic problem. Translating Leland's analyses in terms of our model, we wish to know if there exists a $B' = \frac{1}{1+\rho'}$ such that the solution to the certainty problem

$$\max_{E_t} \sum_{t=0}^{\infty} B'^t \left[U(R(X_t, E_t))\right] \bar{\Delta}$$

$$\text{subject to } X_{t+1} = X_t + [(a - bX_t)X_t - kX_tE_t]\bar{\Delta} \tag{7a}$$

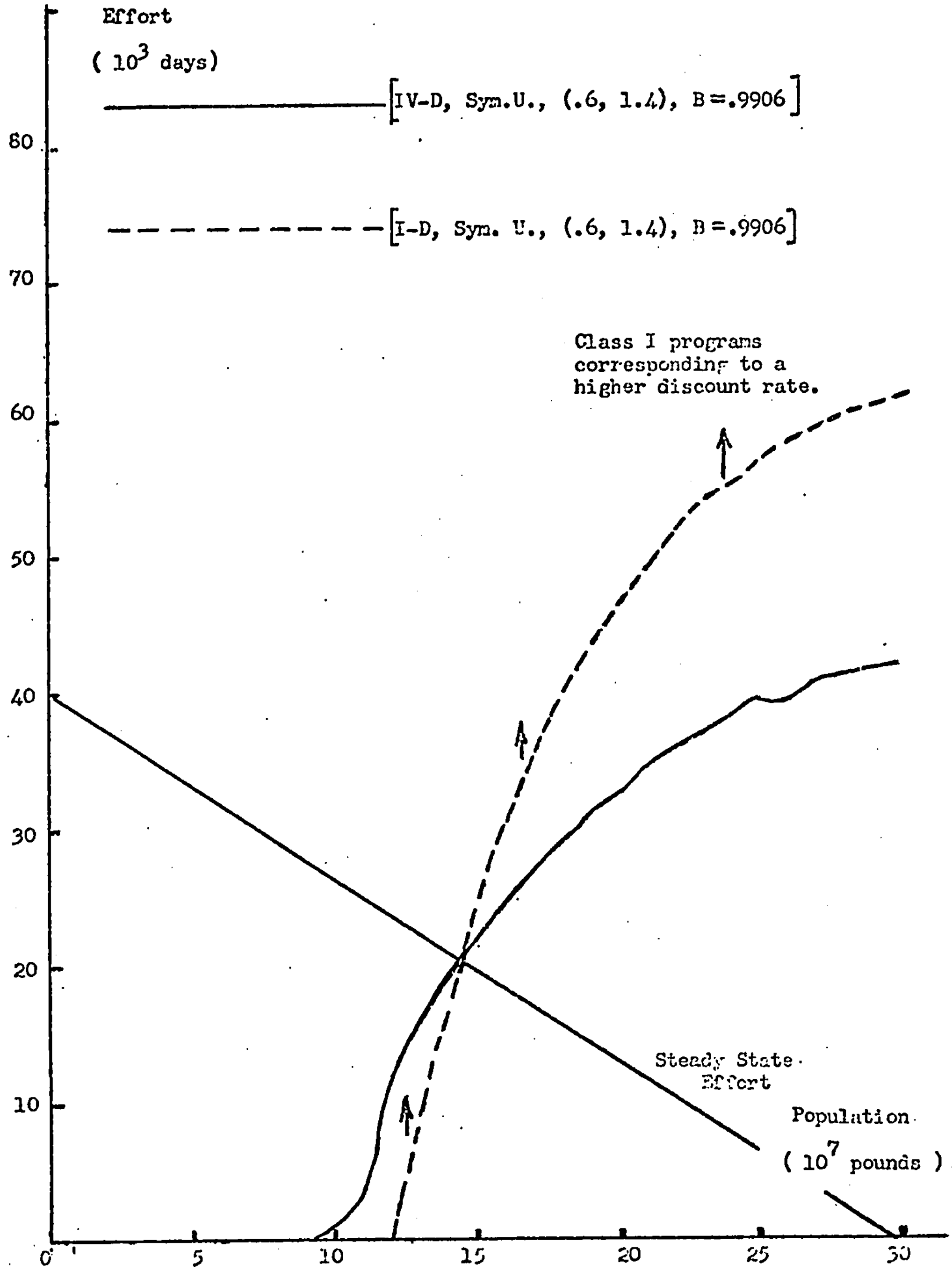

Figure IV-10a. Alternative Risk Adjusted Programs with Variable Depletion Rates for Classes I and IV

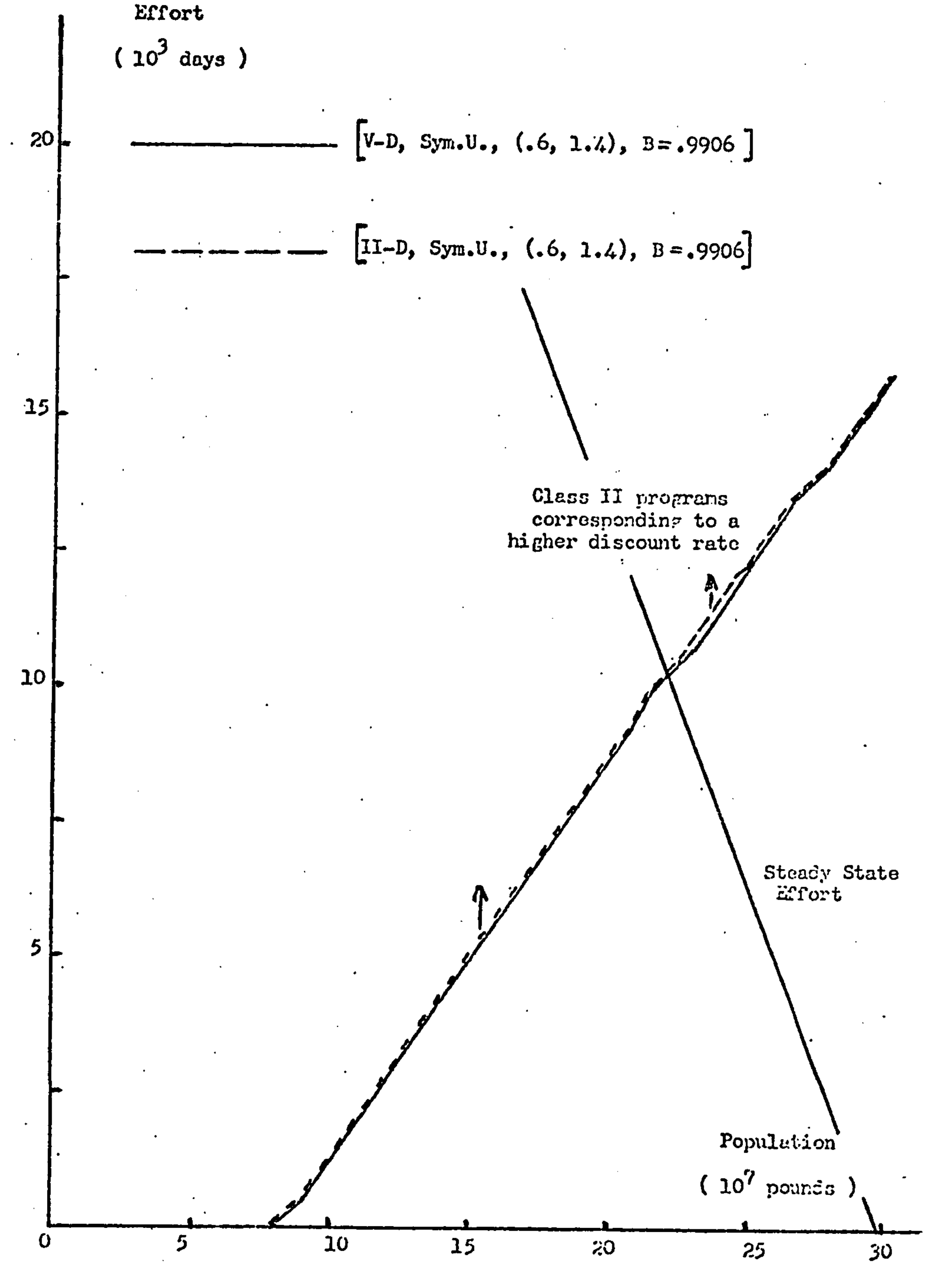

Figure IV-10b. Alternative Risk Adjusted Programs with Variable Depletion Rates for Classes II and V

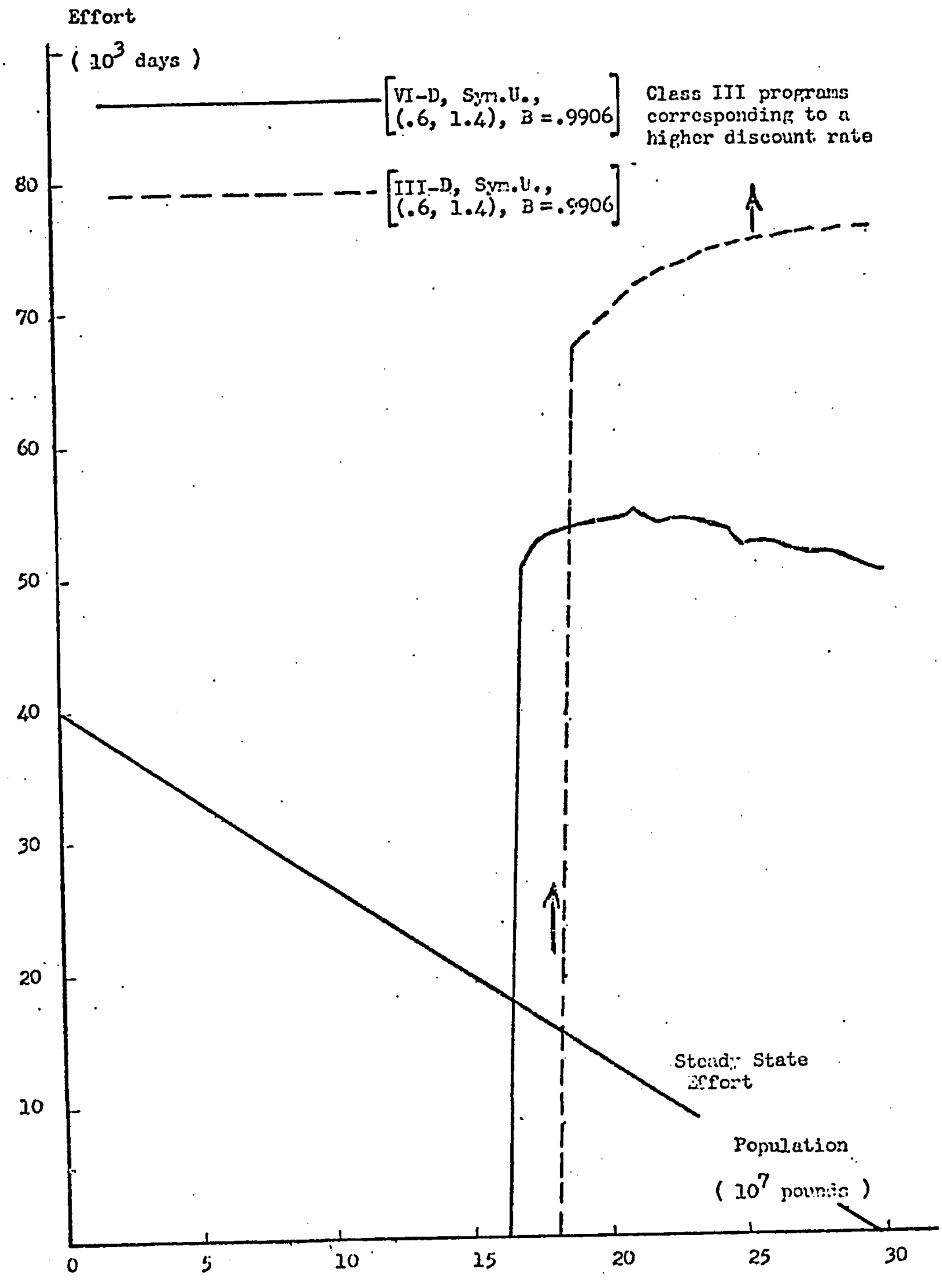

Figure IV-10c. Alternative Risk Adjusted Programs with Variable Depletion Rates for Classes III and VI yields a set of E_t's which are optimal for the stochastic problem

$$\max_{E_t} \sum_{t=0}^{\infty} B^t \mathcal{E}[U(R(X_t, E_t))]\bar{\Delta}$$

$$\text{subject to } X_{t+1} = X_t + [\eta_{1t}(a - bX_t)X_t - \eta_{2t} kX_t E_t]\bar{\Delta} \tag{7b}$$

Notice the same utility function is employed in (7a) and (7b) but in (7a) the discount rate is adjusted to account for stochastic variation in the fishery.

Referring to Observation 5, the optimal effort allocation is greater at small populations and less at large populations with stochastic programs (for either price variation or depletion and growth rate variation) than it is for deterministic programs. Note, however, that the optimal effort levels for the deterministic program increase for all population sizes as the discount rate is adjusted upward to account for risk. Consequently, the simple approach of solving the certainty problem with the risk modified discount rate will not yield the optimal consumption strategy for the corresponding stochastic problem.

D. 4. Concluding Remarks

Unfortunately, in our model, the simple approach of increasing the discount rate to capture risk is not operable. The reason for this is clear. Risk is not a simple compounding function of time and so no overall adjustment in the interest rate is suitable. Of course, there is nothing to preclude us from using a different rate for discounting returns in each period. The calculation of these rates would require knowledge of the variation in returns which is proportional to the expected catch in each period. However since this information is available, only after the optimal consumption programs have been determined, the use of different discount rates to adjust for risk is not practical.

The difficulties with trying to account for risk through the discount rate are of course not peculiar to our analysis. They occur whenever the risk associated with a particular project or activity is not a simple compounding function of time. The variation in net social returns for many consumption and production processes depends on the level of the activity and not on the time during which it occurs. For these types of projects, the use of risk adjusted discounting is clearly inappropriate.

E. QUESTION 4

Question 4: Based on the analysis of Questions 1-3 and our results concerning optimal resource allocation for the fishery in a stochastic environment, what practical policy recommendations can be made for the yellowfin tuna fishery? In particular, (1) how does the policy of maximizing the sustained physical yield from the fishery compare with optimal stochastic policies, (2) do the solutions to deterministic problems yield a sufficiently good approximation to the stochastic solutions to ignore probabilistic modeling all together, and (3) what additional information and data on the biological and economic processes of the fishery would be most useful for resource management?

E.1. Evaluation of Maximum Sustained Yield Policy under Stochastic Conditions

In the policy discussion of Chapter III we concluded that maximum physical yield policies are not optimal for fishery management under deterministic conditions. The same conclusion holds with regard to managing the fishery under stochastic conditions. With continual variations in the growth and the depletion rates, the population is rarely, if ever, in a steady state. The maximum sustained yield policy is deficient in that it abstracts from the non steady state or transient behavior of the fishery. However, even if the population tends to fluctuate around a certain stock size, as it does for Class I, II, IV, and V programs, this stock value will generally differ from the maximum sustained yield population. Of course, the concepts of steady state or maximum yield fishing are not applicable to Class III and VI programs since cyclical fishing is optimal.

E.2. Deterministic Results as an Approximation to Stochastic Solutions

Until only recently, Economist in particular, and Social Scientists in general, have avoided an explicit treatment of probabilistic models. Instead they have relied on deterministic results to provide an approximation for stochastic solutions. The reasons for this are clear. When uncertainty is introduced into the analysis, the formulation of and solution to most problems becomes more involved and sometimes unmanageable. Finally, once the problem is resolved, the results of the stochastic model are often of a subtle and obscure nature and consequently are difficult to interpret for the policy maker. Besides this, there is the widely held belief that most conclusions of deterministic studies remain basically the same when a stochastic treatment is employed. Indeed, if the probabilistic answer to problems differs only slightly from the deterministic solution the large investment required for analyzing stochastic models may not be warranted.

However, regardless of the extent to which solutions differ, the adoption of stochastic methods is desirable if they effect an increase in the social returns from the resource that exceeds the attendant costs of research. Formalizing this notion we define the present value of the resource,

$$V^d(X_0) = \sum_{t=0} B^t \mathcal{E}[U(R(X_t, E^d(X_t)))] \bar{\Delta}$$

to be the expected value of the sum of discounted utilities attainable from an initial population X_0 and following a policy denoted by 'd'. A policy is a rule or strategy for selecting an effort allocation depending on the size of population, such that $E_t^d = E_t^d(X_t)$. Assume 'D' is the optimal deterministic policy chosen to

$$\max_{d} \sum_{t=0}^{\infty} B^t [U(R(X_t, E_t^d(X_t)))] \bar{\Delta}$$

where price is non random, and (9)

$$X_{t+1} = X_t + [(a - bX_t)X_t - kX_t E_t] \bar{\Delta}$$

Let 'S' be the optimum stochastic strategy chosen to

$$\max_{d} \sum_{t=0}^{\infty} B^t \mathcal{E} [U(R(X_t, E_t^d(X_t)))] \bar{\Delta}$$

where price may vary, and (10)

$$X_{t+1} = X_t + [\eta_{1t}(a - bX_t)X_t - \eta_{2t} kX_t E_t] \bar{\Delta}$$

For a probabilistic environment, the increase in present value achieved by employing an optimal stochastic policy, S, rather than the deterministic consumption rule, D, is

$$V^S(X_0) - V^D(X_0) . \qquad (11)$$

Obviously, we are not prepared to recommend whether or not stochastic modeling of the yellowfin tuna industry is warranted based on the type of cost-benefit criteria suggested above. Information on the empirical structure of the fishery is incomplete, and the programs we are investigating only simulate hypothetical situations in the fishery. Yet the following observations should provide us with a useful starting point for future policy analysis.

Observation 7: For the uncertainty programs P, D, $\overline{DG}$, and DG the increases in the present value of the resource for a given initial population realized by employing the optimal stochastic policy is

a) greatest for Classes I, III, IV, and VI and almost negligible for Classes II and V,

b) increases with larger initial populations and,

c) increases with greater variations in either price or the growth and depletion rates.

Examples of present value increases, calculated by equation (11) and corresponding to Classes I and III for variable depletion rate programs are plotted in Figures IV-11a, b. The additions to present value for Class II programs are only of the order of magnitude of 10^3 dollars. Because our computer print outs were only designed to report numerical results up to five significant figures, the Class II figures are too small to report accurately. Similar computations for Classes IV - VI are not included here because they are more difficult to interpret, since present value figures are in terms of natural logs.

Looking at Figures IV-11a, b we see that present value increases are substantial for Classes I and III, that they increase according to the initial population size and that they become larger as the rate of depletion is more uncertain.[12] As a general result, it is not surprising to find that the magnitude of the present value increase depends on the extent to which optimal stochastic and deterministic policies differ. This explains the small increase for Classes II and V,

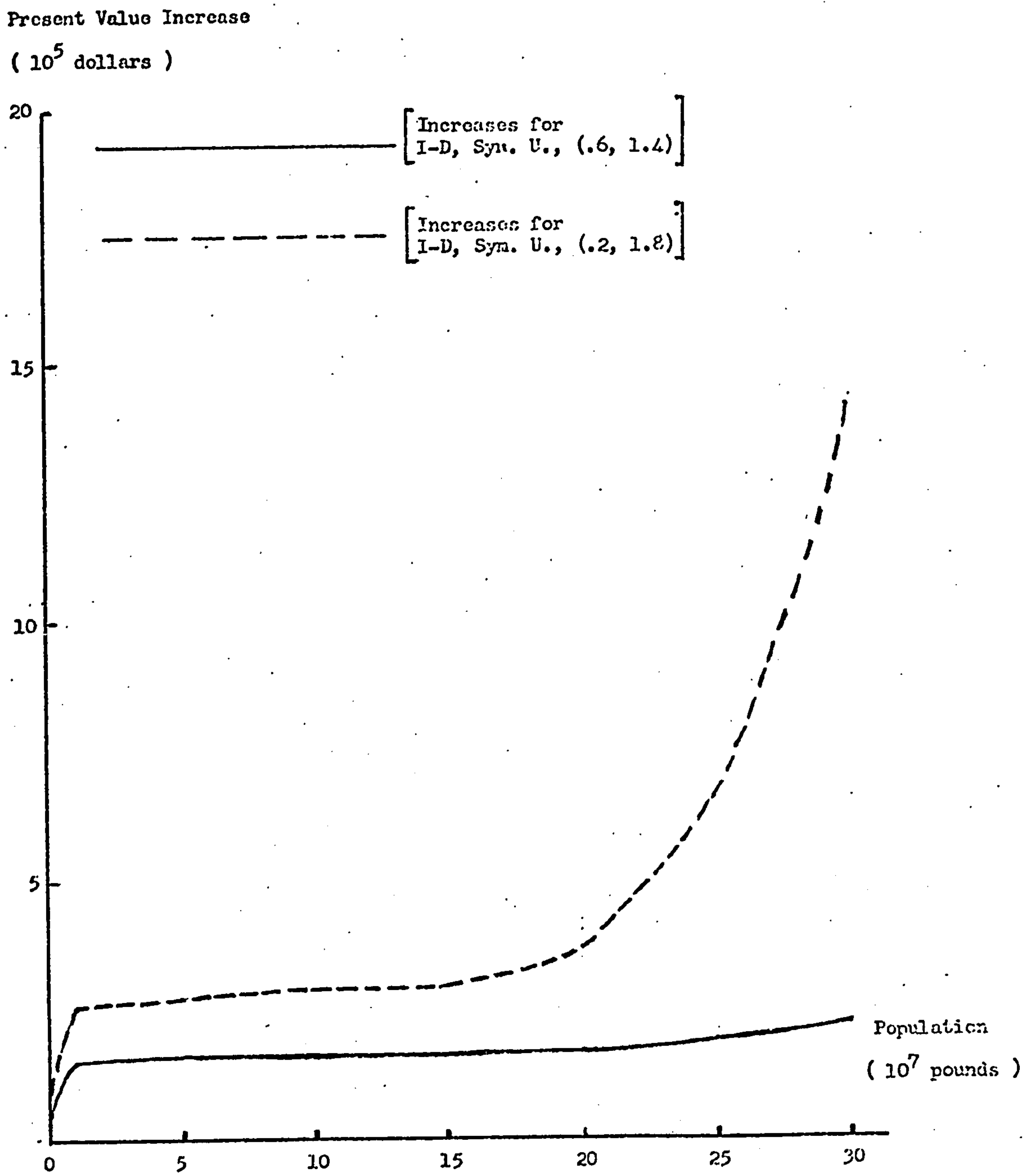

Figure IV-11a. Present Value Increases for Class I Programs with Variable Depletion Rates

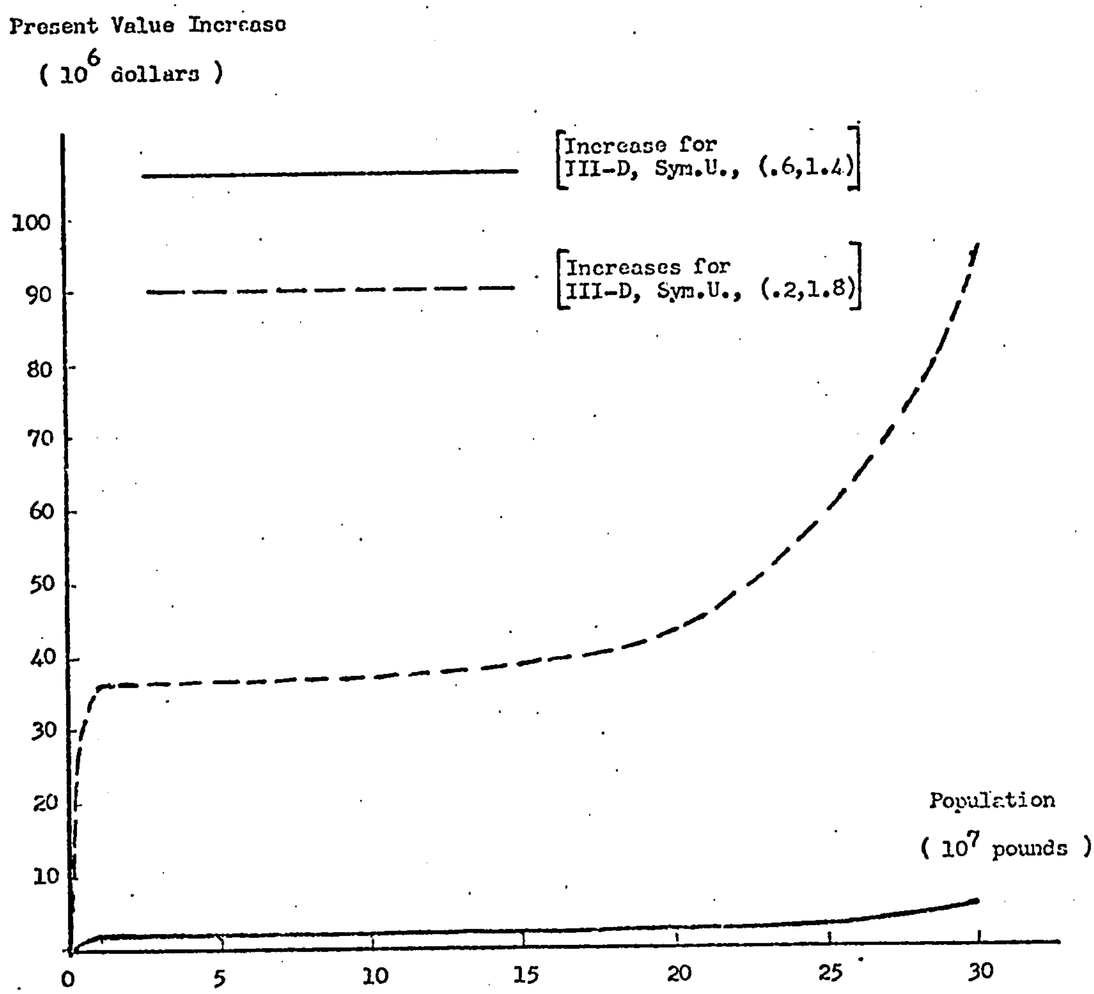

Figure IV-11b. Present Value Increases for Class III Programs with Variable Depletion Rates and that the increase in present values are larger for programs subject to more uncertainty.

At least for the range of parameter values we have analyzed, solutions to deterministic problems serve as excellent approximations for stochastic solutions in the Class II and V cases. On the other hand, our tentative conclusion for Classes I, III, IV, and VI is that a probabilistic treatment of the resource allocation problem is needed since deterministic consumption rules are poor substitutes for optimal stochastic strategies.

E.3. Suggestions for Additional Empirical Analysis

With our Markov model we have been able to assess the impact of various resource allocation programs on the fishery for a variety of different environmental and economic conditions. In effect, new policies and decision rules for operating the fishery have been tested under simulated conditions without running the risk of experimenting on the real systems. At the same time, our knowledge of the empirical structure of the fishery is only fragmentary. On the biological side, the nature of the variations in growth and depletion rates are as yet unknown, and on the economic side, information on the cost of fishing effort and the social attitudes toward risk bearing is incomplete.

Hopefully though, this study has yielded some valuable insights into which variables are more important than others in the analysis of the fishery and which topics deserve the highest priority in future research endeavors. We have observed that optimal decision rules for operating the fishery are more sensitive to changes in certain variables and components of the model than others. This sort of information indicates the types of biological and economic data that will prove to be most useful for managing the fishery.

a. Biological Data

Without knowing the frequency functions for the rate of growth and depletion parameters, η_1 and η_2 we have assumed that they are distributed according to a uniform or triangular density function. If these serve as good approximations for the real distributions of η_1 and η_2 then our results indicate that we should be most concerned with gathering data to determine the range over which these parameters vary. We have observed that the optimal consumption strategies are sensitive to the amount of variations in these parameters. On the other hand, the type of distribution, whether it be uniform or triangular, symmetric or skewed does not seem to effect the optimal decision rules significantly.

b. Economic Research

Our results indicate that optimal allocation policies differ according to the specification of the cost of effort function. In estimating costs it will be particularly interesting to determine if marginal costs increase with greater allocations of effort, as is the case for Classes II and V. Under these conditions we observed that deterministic or certainty equivalent policies provide excellent approximations to optimal stochastic decision rules for the fishery.

One should realize that in gathering cost data, for our purposes effort is defined biologically in terms of efficiency units. It is a type of aggregate input which when applied to the fishery will remove or catch, on average, a certain percentage of the population. The components comprising a unit of effort need to be specified in order to estimate the quantity of capital goods and labor services used in the fishing process. Additionally, as with all cost estimations, some care is needed to insure that one is measuring the true opportunity cost of inputs rather than the accounting cost. This is particularly important in the yellowfin fishery, since the boats operating in this industry have a number of alternative opportunities for employment in other fisheries as well.

Optimal decision rules are also sensitive to society's attitudes toward risk bearing. Our approach has been to represent risk preferences in the form of the social welfare function as opposed to the more common, but as we argued less valid procedure of adjusting for risk through the social discount rate. The problem of actually estimating and providing a consistent representation of social risk preferences is a very difficult one, and we shall not attempt to resolve it here. The object of our study is much more modest: to determine the effect of different attitudes for risk bearing on optimal resource allocation in the fishery. Beyond this, however, we have a few comments pertaining to the choice of the social welfare function.

Naturally the social attitudes towards variations in fishery rents will depend on how these rents are distributed among individuals in the economy, or for the case of an international fishery, how they are dispersed among the member countries. Consequently, implicit in the choice of a social utility function must be some provision for distribution of the fishery rents. At the same time, a number of regulatory schemes to prevent individuals from over exploiting the fishery have been proposed, including quota and licensing systems, each resulting in a different distribution of rents. This suggests that the two problems of: (1) formulating optimal consumption rules based on maximizing expected social utility and, (2) devising schemes to enforce these rules, must be solved simultaneously, as they are interrelated. The type of regulatory procedure will have an impact on distribution, which in turn will effect the choice of the social welfare function.

Once the means for dividing the returns has been established the problem of choosing a welfare function that reflects social risk preferences still remains. The idea of constructing an aggregated social welfare function from a weighted sum of individual utility functions is perhaps theoretically possible, but impractical. It appears to us that the ohoice might best be made politically. For example, using our Markov Decision model, one could determine various optimal allocation plans for the fishery derived by maximizing different social welfare criteria. These plans could then be reviewed and voted on by an electorate composed of individuals (countries), who were to receive a share of the rents from the fishery.

F. SUMMARY STATEMENTS

The effect of uncertainty regarding prices, and growth and depletion rates on optimal allocation strategies have been analyzed for situations where society is averse and indifferent to variations in the returns from the fishery. The impact of uncertainty on consumption programs is directly related to the amount of variation in fishery rents determined by the size of the expected catch and the degree of fluctuation in the price and depletion rates. The variability of rents increases with population since the expected catch is typically greater. Key changes in optimal effort allocations occurring in a stochastic environment for different populations are of the following form:

For the risk neutral social planner, the allocation of effort and the resultant expected catch tend to remain constant or decrease as the price and growth and depletion rates become more uncertain. The largest changes in effort take place at the upper end of the population scale. The risk averse fishery manager increases effort at small populations to take advantage of the small fluctuations in rents, and decreases effort for larger populations to avoid greater risk in returns. The effect of uncertainty on optimal Class II and V programs is relatively insignificant since the allocations of effort, expected catches, and thus the fluctuations in rents are small compared to the other classes.

The qualitative nature of our results are the same for all different forms of the frequency function analyzed. The most important element of the parameter distributions affecting allocation strategies is the range over which the variables are allowed to fluctuate. Optimal effort allocations corresponding to variable depletion rate cases are affected only slightly by allowing simultaneous variation in the natural growth rate.

The policy implications evolving from this analysis are: (1) The policy of maximizing the sustainable physical yield from the fishery, currently followed by the Tuna Commission, is not an efficient device for allocating resources under deterministic or stochastic conditions. The policy should be retained only if the political and social costs of switching to a new program are prohibitive. (2) Using the discount rate to capture risk is inappropriate since risk is not a simple compounding function of time and no overall adjustment in the interest rate is suitable. (3) Solutions to deterministic problems serve as excellent approximations for stochastic solutions in Class II and V cases. However, for the other classes a probabilistic treatment of the resource allocation problem is needed since deterministic consumption rules are poor substitutes for optimal stochastic strategies.

APPENDIX IV

Optimal Effort Allocations

Contents:

DETERMINISTIC PROGRAMS

PROGRAM:

Population (10^7 pounds)	(I-DET.) Effort Allocation (days)	(II-DET) Effort Allocation (days)	(III-DET) Effort Allocation (days)
0	0	0	0
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	500	0
10	0	1,250	0
11	0	2,000	0
12	1,750	2,750	0
13	12,000	3,500	0
14	20,500	4,250	0
15	27,500	5,000	0
16	33,750	5,750	0
17	39,000	6,500	0
18	43,500	7,250	0
19	47,250	8,000	74,250
20	50,750	8,750	76,250
21	53,750	9,500	78,000
22	56,250	10,000	79,500
23	58,500	11,000	80,750
24	60,250	11,750	81,750
25	62,000	12,250	87,500
26	63,500	13,250	87,750
27	64,500	13,750	88,250
28	65,750	14,500	88,250
29	66,500	15,250	88,500
30	67,250	16,000	88,500

PROGRAM:

Population (10^7 pounds)	(IV-DET.) Effort Allocation (days)	(V-DET.) Effort Allocation (days)	(VI-DET.) Effort Allocation (days)
0	0	0	0
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	500	0
10	250	1,250	0
11	1,500	2,000	0
12	12,500	2,750	0
13	12,250	3,500	0
14	20,500	4,250	0
15	23,500	5,000	0
16	25,750	5,750	0
17	27,750	6,500	54,000
18	29,500	7,250	57,500
19	34,000	8,000	58,500
20	33,000	8,750	57,250
21	35,500	9,500	59,750
22	35,750	10,000	57,250
23	36,500	11,000	58,500
24	39,000	11,750	58,000
25	40,000	12,250	55,000
26	39,000	13,000	53,750
27	41,000	13,750	45,750
28	42,500	14,500	47,500
29	41,000	15,000	48,500
30	41,750	16,000	47,250

CLASS I PROGRAMS

PROGRAM:

I-D, Sym.U.	(.8, 1.2)	(.6, 1.4)	(.4, 1.6)	(.2, 1.8)
Population (10^7 pounds)	Effort Allocation (days)			
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
11	0	0	0	0
12	1,750	1,500	1,500	1,750
13	10,750	10,000	10,000	11,250
14	18,250	17,500	18,500	18,000
15	24,500	25,000	24,250	24,000
16	30,750	30,750	30,000	28,750
17	36,250	35,750	34,500	32,750
18	41,250	40,000	38,250	36,500
19	45,250	43,750	41,750	39,250
20	48,500	46,750	43,750	41,750
21	51,250	49,500	46,750	43,750
22	54,000	52,000	48,750	45,500
23	56,250	54,000	50,500	47,[illegible]00
24	58,250	55,500	52,000	48,250
25	60,000	57,000	53,250	49,250
26	61,250	58,250	54,250	50,000
27	62,500	59,250	55,250	50,750
28	63,500	60,250	55,750	51,500
29	64,250	60,750	56,500	52,000
30	65,000	61,500	56,750	52,250

PROGRAM:

I-D, Sym.	(.8, 1.2)	(.6, 1.4)	(.4, 1.6)	(.2, 1.8)
Population (10^7 pounds)	Effort Allocation (days)			
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
11	0	0	0	0
12	1,750	1,750	1,500	1,500
13	11,250	10,500	10,250	10,250
14	19,000	18,000	17,750	18,000
15	25,750	25,000	24,750	24,500
16	31,500	31,000	30,500	30,000
17	36,500	36,250	35,500	34,250
18	41,250	40,750	39,750	38,500
19	45,250	44,500	43,250	41,750
20	48,750	47,750	46,500	44,500
21	51,750	50,750	49,000	47,000
22	54,250	53,250	51,250	49,000
23	56,500	55,250	53,250	50,750
24	58,500	57,000	54,750	52,000
25	60,250	58,750	56,250	53,250
26	61,750	60,000	57,500	54,250
27	63,000	61,250	58,500	55,250
28	64,000	62,000	59,250	56,000
29	64,750	63,000	60,000	56,500
30	65,500	63,500	60,500	57,000

PROGRAM:

I-D, Skd. R. (.8, 1.5) (.8, 1.7) (.8, 1.9)

Population (10^7 pounds)	Effort Allocation (days)		
	(.8, 1.5)	(.8, 1.7)	(.8, 1.9)
0	0	0	0
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	0
10	0	0	0
11	0	0	0
12	1,750	1,750	1,750
13	10,250	10,500	10,500
14	17,750	18,000	17,250
15	24,000	27,000	23,500
16	30,750	30,750	30,250
17	36,250	36,000	35,500
18	40,750	40,000	39,250
19	44,500	43,500	42,500
20	47,500	46,500	45,500
21	50,500	49,250	48,250
22	53,000	51,500	50,000
23	55,000	53,500	51,750
24	56,750	55,000	53,250
25	58,250	56,500	54,500
26	59,500	57,500	55,000
27	60,500	58,500	56,250
28	61,500	59,250	57,000
29	62,250	60,000	57,500
30	62,750	60,500	57,750

PROGRAM:

I-D, Skd. L.	(.6, 1.2)	(.4, 1.2)	(.2, 1.2)
Population (10^7 pounds)	Effort Allocation (days)		
0	0	0	0
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	0
10	0	0	0
11	0	0	0
12	1,750	1,750	1,750
13	10,500	10,500	10,500
14	18,000	18,000	18,000
15	24,750	24,500	24,500
16	30,750	30,500	30,250
17	36,000	35,750	35,250
18	40,750	40,500	40,000
19	45,000	44,750	44,250
20	48,250	48,000	47,750
21	51,000	50,750	50,250
22	53,500	53,000	52,750
23	55,750	55,250	54,750
24	57,750	57,250	56,500
25	59,500	59,000	58,250
26	61,000	60,500	59,500
27	62,250	61,750	61,000
28	63,000	62,750	62,000
29	64,000	63,500	63,000
30	64,500	64,000	63,500

PROGRAM:

I-$\overline{DG}$, Sym.U.	(.8, 1.2)	(.6, 1.4)	(.4, 1.6)	(.2, 1.8)
Population (10^7 pounds)	Effort Allocation (days)			
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
11	0	0	0	0
12	0	0	1,500	3,250
13	11,000	10,250	10,000	10,750
14	20,500	20,500	20,500	20,500
15	26,750	25,750	25,250	24,500
16	32,000	30,500	29,750	28,750
17	36,500	35,500	34,500	33,250
18	40,750	40,000	38,500	36,500
19	44,750	43,750	42,000	40,000
20	48,500	47,000	45,000	42,250
21	51,500	49,750	57,250	44,500
22	54,000	52,000	49,500	46,250
23	56,000	54,000	51,000	47,500
24	58,000	55,750	52,250	48,750
25	59,750	57,250	53,500	49,500
26	61,250	58,250	54,250	50,250
27	62,500	59,250	55,000	50,750
28	63,250	60,000	55,500	51,000
29	64,250	60,500	56,000	51,250
30	64,750	61,000	56,250	51,250

PROGRAM:

I-$\overline{DG}$, Sym.	(.8, 1.2)	(.6, 1.4)	(.4, 1.6)	(.2, 1.8)
Population (10^7 pounds)	Effort Allocation (days)			
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
11	0	0	0	0
12	500	0	250	1,250
13	11,250	10,750	10,750	10,500
14	20,500	20,500	20,500	20,500
15	27,000	26,500	27,000	25,500
16	32,500	31,500	30,750	30,250
17	37,250	36,250	35,750	34,750
18	41,500	40,750	40,000	38,750
19	45,250	44,500	43,500	42,250
20	48,750	48,000	46,750	45,250
21	51,750	50,750	49,500	47,500
22	54,250	53,250	51,500	49,500
23	56,500	55,500	53,500	51,250
24	58,500	57,250	55,000	52,500
25	60,000	58,750	56,500	53,750
26	61,500	60,000	57,500	54,500
27	62,750	61,000	58,250	55,250
28	64,000	62,000	59,000	55,750
29	64,750	62,750	59,500	56,000
30	65,500	63,250	60,000	56,250

PROGRAM:

I-$\overline{DG}$, Skd. R. (.8, 1.5) (.8, 1.7) (.8, 1.9)

Population (10^7 pounds)	Effort Allocation (days)		
	(.8, 1.5)	(.8, 1.7)	(.8, 1.9)
0	0	0	0
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	0
10	0	0	0
11	0	0	0
12	0	0	0
13	10,500	10,250	10,250
14	20,500	20,500	20,500
15	26,500	26,250	26,000
16	31,500	31,000	30,750
17	35,750	35,250	35,000
18	40,500	40,500	40,000
19	44,750	44,250	44,000
20	48,000	47,500	46,750
21	50,750	49,750	48,750
22	53,000	52,000	51,000
23	55,250	54,000	52,750
24	57,000	55,000	53,750
25	58,500	56,750	55,000
26	59,500	57,750	56,000
27	60,500	58,750	56,500
28	61,500	59,250	57,000
29	62,000	59,750	57,250
30	62,500	60,000	57,500

PROGRAM:

I-$\overline{DG}$, Skd. L.	(.6, 1.2)	(.4, 1.2)	(.2, 1.2)
Population (10^7 pounds)	Effort Allocation (days)		
0	0	0	0
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	0
10	0	0	0
11	0	0	0
12	0	0	500
13	11,000	11,000	11,500
14	20,500	20,500	20,500
15	26,500	26,500	26,500
16	31,750	31,500	31,500
17	36,500	36,250	36,000
18	40,750	40,250	40,000
19	44,500	44,000	43,500
20	48,000	47,250	46,750
21	51,250	50,500	49,750
22	53,750	53,250	52,500
23	55,750	55,250	54,750
24	57,500	57,000	56,500
25	59,250	58,500	58,000
26	60,750	60,000	59,250
27	62,000	61,250	60,250
28	63,000	62,250	61,500
29	63,750	63,250	62,250
30	64,500	63,750	63,000

PROGRAM:

I-DG, Sym.U. (.8, 1.2) (.6, 1.4) (.4, 1.6) (.2, 1.8)

Population (10^7 pounds)	Effort Allocation (days)			
	(.8, 1.2)	(.6, 1.4)	(.4, 1.6)	(.2, 1.8)
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
11	0	0	0	0
12	0	0	0	3,250
13	9,250	9,500	10,250	11,250
14	17,500	17,750	18,000	18,000
15	25,000	24,750	24,250	23,750
16	31,000	30,750	29,750	28,500
17	36,500	35,500	34,000	32,250
18	41,000	39,750	38,000	35,750
19	45,000	43,500	41,250	38,750
20	48,000	46,750	44,250	41,250
21	51,250	49,500	46,500	43,250
22	54,000	51,750	48,500	45,250
23	56,250	53,750	50,250	46,750
24	58,000	55,500	51,750	48,000
25	59,750	57,000	53,000	49,000
26	61,250	58,250	54,250	50,000
27	62,250	59,250	55,000	50,750
28	63,500	60,250	55,750	51,250
29	64,250	60,750	56,250	51,750
30	65,000	61,250	56,750	52,250

CLASS II PROGRAMS

PROGRAM:

Population (10^7 pounds) II-D, Sym.U.	Effort Allocation (days) (.8, 1.2)	(.6, 1.4)	(.4, 1.6)	(.2, 1.8)
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	500	500	500	500
10	1,250	1,250	1,250	1,250
11	2,000	2,000	2,000	2,000
12	2,750	2,750	2,750	2,750
13	3,500	3,500	3,500	3,500
14	4,250	4,250	4,250	4,250
15	5,000	5,000	5,000	5,000
16	5,750	5,750	5,750	5,750
17	6,500	6,500	6,500	6,500
18	7,250	7,250	7,250	7,500
19	8,000	8,000	8,000	8,000
20	8,750	8,750	8,750	8,750
21	9,500	9,500	9,500	9,500
22	10,250	10,250	10,250	10,250
23	11,000	11,000	11,000	11,000
24	11,750	11,750	11,750	11,500
25	12,500	12,250	12,250	12,250
26	13,000	13,000	13,000	13,000
27	13,750	13,750	13,750	13,750
28	14,500	14,500	14,500	14,500
29	15,250	15,250	15,250	15,250
30	16,000	16,000	16,000	16,000

PROGRAM:

II-D, Syn.	(.8, 1.2)	(.6, 1.4)	(.4, 1.6)	(.2, 1.8)
Population (10^7 pounds)	Effort Allocation (days)			
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	500	500	500	500
10	1,250	1,250	1,250	1,250
11	2,000	2,000	2,000	2,000
12	2,750	2,750	2,750	2,750
13	3,500	3,500	3,500	3,500
14	4,250	4,250	4,250	4,250
15	5,000	5,000	5,000	5,000
16	5,750	5,750	5,750	5,750
17	6,500	6,500	6,500	6,500
18	7,250	7,250	7,250	7,250
19	8,000	8,000	8,000	8,000
20	8,750	8,750	8,750	8,750
21	9,500	9,500	9,500	9,500
22	10,250	10,250	10,250	10,250
23	11,000	11,000	11,000	11,000
24	11,750	11,750	11,750	11,750
25	12,250	12,500	12,250	12,250
26	13,250	13,000	13,000	13,000
27	13,750	13,750	13,750	13,750
28	14,500	14,500	14,500	14,500
29	15,250	15,250	15,250	15,250
30	16,000	16,000	16,000	16,000

PROGRAM:

II-D, Skd.R.	(.8, 1.5)	(.8, 1.7)	(.8, 1.9)
Population (10^7 pounds)	Effort Allocation (days)		
0	0	0	0
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	500	500	500
10	1,250	1,250	1,250
11	2,000	2,000	2,000
12	2,750	2,750	2,750
13	3,500	3,500	3,500
14	4,250	4,250	4,250
15	5,000	5,000	5,000
16	5,750	5,750	5,750
17	6,500	6,500	6,500
18	7,250	7,250	7,250
19	8,000	8,000	8,000
20	8,750	8,750	8,750
21	9,500	9,500	9,500
22	10,250	10,250	10,250
23	11,000	11,000	11,000
24	11,750	11,750	11,750
25	12,500	12,500	12,500
26	13,000	13,000	13,000
27	13,750	13,750	13,750
28	14,500	14,500	14,500
29	15,250	15,250	15,250
30	16,000	16,000	16,000

PROGRAM:

II-D, Skd. L.	(.6, 1.2)	(.4, 1.2)	(.2, 1.2)
Population (10^7 pounds)	Effort Allocation (days)		
0	0	0	0
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	500	500	500
10	1,250	1,250	1,250
11	2,000	2,000	2,000
12	2,750	2,750	2,750
13	3,500	3,500	3,500
14	4,250	4,250	4,250
15	5,000	5,000	5,000
16	5,750	5,750	5,750
17	6,500	6,500	6,500
18	7,250	7,250	7,250
19	8,000	8,000	8,000
20	8,750	8,750	8,750
21	9,500	9,500	9,500
22	10,250	10,250	10,250
23	11,000	11,000	11,000
24	11,750	11,750	11,750
25	12,500	12,500	12,500
26	13,000	13,000	13,000
27	13,750	13,750	13,750
28	14,500	14,500	14,500
29	15,250	15,250	15,250
30	16,000	16,000	16,000

PROGRAM:

II-$\overline{DG}$, Sym.U.	(.8, 1.2)	(.6, 1.4)	(.4, 1.6)	(.2, 1.8)
Population (10^7 pounds)	Effort Allocation (days)			
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	500	500	500	500
10	1,250	1,250	1,250	1,250
11	2,000	2,000	2,000	2,000
12	2,750	2,750	2,750	2,750
13	3,500	3,500	3,500	3,500
14	4,250	4,250	4,250	4,250
15	5,000	5,000	5,000	5,000
16	5,750	5,750	5,750	5,750
17	6,500	6,500	6,500	6,500
18	7,250	7,250	7,250	7,250
19	8,000	8,000	8,000	8,000
20	8,750	8,750	8,750	8,750
21	9,500	9,500	9,500	9,500
22	10,000	10,000	10,000	10,000
23	11,000	11,000	11,000	11,000
24	11,750	11,750	11,750	11,750
25	12,250	12,500	12,500	12,250
26	13,250	13,000	13,000	13,000
27	13,750	13,750	13,750	13,750
28	14,500	14,500	14,500	14,500
29	15,250	15,250	15,250	15,250
30	16,000	16,000	16,000	16,000

PROGRAM:

II-$\overline{DG}$, Sym.	(.8, 1.2)	(.6, 1.4)	(.4, 1.6)	(.2, 1.8)
Population (10^7 pounds)	Effort Allocation (days)			
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	500	500	500	500
10	1,250	1,250	1,250	1,250
11	2,000	2,000	2,000	2,000
12	2,750	2,750	2,750	2,750
13	3,500	3,500	3,500	3,500
14	4,250	4,250	4,250	4,250
15	5,000	5,000	5,000	5,000
16	5,750	5,750	5,750	5,750
17	6,500	6,500	6,500	6,500
18	7,250	7,250	7,250	7,250
19	8,000	8,000	8,000	8,000
20	8,750	8,750	8,750	8,750
21	9,500	9,500	9,500	9,500
22	10,000	10,000	10,000	10,000
23	11,000	11,000	11,000	11,000
24	11,750	11,750	11,750	11,750
25	12,250	12,250	12,500	12,500
26	13,250	13,000	13,000	13,000
27	13,750	13,750	13,750	13,750
28	14,500	14,500	14,500	14,500
29	15,250	15,250	15,250	15,250
30	16,000	16,000	16,000	16,000

PROGRAM:

II-$\overline{DG}$, Skd. R. (.8, 1.5) (.8, 1.7) (.8, 1.9)

Population (10^7 pounds)	Effort Allocation (days)		
0	0	0	0
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	500	500	500
10	1,250	1,250	1,250
11	2,000	2,000	2,000
12	2,750	2,750	2,750
13	3,500	3,500	3,500
14	4,250	4,250	4,250
15	5,000	5,000	5,000
16	5,750	5,750	5,750
17	6,500	6,500	6,500
18	7,250	7,250	7,250
19	8,000	8,000	8,000
20	8,750	8,750	8,750
21	9,500	9,500	9,500
22	10,000	10,000	10,000
23	11,000	11,000	11,000
24	11,750	11,750	11,750
25	12,250	12,250	12,250
26	13,000	13,000	13,000
27	13,750	13,750	13,750
28	14,500	14,500	14,500
29	15,250	15,250	15,250
30	16,000	16,000	16,000

PROGRAM:

II-$\overline{DG}$, Skd. L.	(.6, 1.2)	(.4, 1.2)	(.2, 1.2)
Population (10^7 pounds)		Effort Allocation (days)	
0	0	0	0
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	500	500	500
10	1,250	1,250	1,250
11	2,000	2,000	2,000
12	2,750	2,750	2,750
13	3,500	3,500	3,500
14	4,250	4,250	4,250
15	5,000	5,000	5,000
16	5,750	5,750	5,750
17	6,500	6,500	6,500
18	7,250	7,250	7,250
19	8,000	8,000	8,000
20	8,750	8,750	8,750
21	9,500	9,500	9,500
22	10,000	10,000	10,000
23	11,000	11,000	11,000
24	11,750	11,750	11,750
25	12,250	12,250	12,250
26	13,250	13,250	13,250
27	13,750	13,750	13,750
28	14,500	14,500	14,500
29	15,250	15,250	15,250
30	16,000	16,000	16,000

PROGRAM:

II-DG, Sym.U.	(.8, 1.2)	(.6, 1.4)	(.4, 1.6)	(.2, 1.8)
Population (10^7 pounds)	Effort Allocation (days)			
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	500	500	500	500
10	1,250	1,250	1,250	1,250
11	2,000	2,000	2,000	2,000
12	2,750	2,750	2,750	2,750
13	3,500	3,500	3,500	3,500
14	4,250	4,250	4,250	4,250
15	5,000	5,000	5,000	5,000
16	5,750	5,750	5,750	5,750
17	6,500	6,500	6,500	6,500
18	7,250	7,250	7,250	7,250
19	8,000	8,000	8,000	8,000
20	8,750	8,750	8,750	8,750
21	9,500	9,500	9,500	9,500
22	10,250	10,250	10,250	10,000
23	11,000	11,000	11,000	10,750
24	11,750	11,750	11,500	11,500
25	12,500	12,250	12,250	12,250
26	13,000	13,000	13,000	13,000
27	13,750	13,750	13,750	13,750
28	14,500	14,500	14,500	14,500
29	15,250	15,250	15,250	15,250
30	16,000	16,000	16,000	16,000

CLASS III PROGRAMS

PROGRAM:

III-D, Sym.U.	(.8, 1.2)	(.6, 1.4)	(.4, 1.6)	(.2, 1.8)
Population (10^7 pounds)	Effort Allocation (days)			
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
11	0	0	0	0
12	0	0	0	0
13	0	0	0	0
14	0	0	0	0
15	0	0	0	0
16	0	0	0	0
17	0	0	0	0
18	0	0	0	0
19	72,750	67,750	61,750	0
20	75,000	69,500	63,750	56,250
21	77,000	71,250	64,750	57,500
22	78,500	72,500	65,500	58,500
23	79,750	73,500	66,250	59,250
24	81,000	74,000	66,750	60,000
25	81,750	74,500	67,000	60,500
26	82,250	75,000	67,250	60,750
27	82,750	75,250	67,500	60,750
28	83,000	75,250	67,500	61,000
29	83,250	75,250	67,500	61,000
30	83,250	75,250	67,250	61,000
				61,000

PROGRAM:

III-D, Sym.	(.8, 1.2)	(.6, 1.4)	(.4, 1.6)	(.2, 1.8)
Population (10^7 pounds)	Effort Allocation (days)			
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
11	0	0	0	0
12	0	0	0	0
13	0	0	0	0
14	0	0	0	0
15	0	0	0	0
16	0	0	0	0
17	0	0	0	0
18	0	0	0	0
19	73,750	70,750	66,750	62,500
20	76,250	73,000	68,750	64,000
21	78,250	74,750	70,000	65,000
22	80,000	76,250	71,250	66,000
23	81,250	77,250	72,000	66,500
24	82,500	78,250	72,750	67,000
25	83,250	78,750	73,000	67,250
26	84,000	79,250	73,250	67,250
27	84,500	79,500	73,500	67,250
28	84,750	79,750	73,500	67,250
29	85,000	79,750	73,250	67,000
30	85,000	79,750	73,250	66,750

PROGRAM:

III-D, Skd.R.	(.8, 1.5)	(.8, 1.7)	(.8, 1.9)
Population (10^7 pounds)	Effort Allocation (days)		
0	0	0	0
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	0
10	0	0	0
11	0	0	0
12	0	0	0
13	0	0	0
14	0	0	0
15	0	0	0
16	0	0	0
17	0	0	0
18	0	0	0
19	70,250	67,500	64,750
20	72,250	69,250	66,000
21	74,000	70,750	67,000
22	75,250	71,650	67,500
23	76,250	72,250	67,750
24	77,000	72,750	67,750
25	77,500	73,000	67,750
26	78,000	73,000	67,250
27	78,250	73,000	66,750
28	78,250	72,750	66,250
29	78,250	72,500	65,750
30	78,000	72,250	65,000

PROGRAM:

III-D, Skd. I.

Population (10^7 pounds)	Effort Allocation (days) (.6, 1.2)	(.4, 1.2)	(.2, 1.2)
0	0	0	0
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	0
10	0	0	0
11	0	0	0
12	0	0	0
13	0	0	0
14	0	0	0
15	0	0	0
16	0	0	0
17	0	0	0
18	0	0	0
19	72,000	70,500	69,500
20	74,500	73,000	71,750
21	76,250	75,250	73,750
22	77,750	76,500	75,750
23	79,000	77,500	76,750
24	80,000	78,250	77,500
25	80,750	79,000	78,250
26	81,500	79,750	78,750
27	81,750	80,000	79,000
28	82,000	80,500	79,250
29	82,250	80,750	79,500
30	82,250	80,750	79,500

PROGRAM:

III-$\overline{DG}$,. Sym.U.	(.8, 1.2)	(.6, 1.4)	(.4, 1.6)	(.2, 1.8)
Population (10^7 pounds)	Effort Allocation (days)			
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
11	0	0	0	0
12	0	0	0	0
13	0	0	0	0
14	0	0	0	0
15	0	0	0	0
16	0	0	0	0
17	0	0	0	0
18	0	0	0	0
19	73,000	69,000	64,750	59,750
20	75,500	71,250	66,000	61,000
21	77,500	72,750	67,000	61,750
22	79,000	73,750	67,750	62,000
23	80,250	74,500	68,000	62,000
24	81,250	75,250	68,250	62,000
25	82,000	75,500	68,000	62,000
26	82,500	75,500	68,000	61,750
27	82,750	75,500	67,750	61,500
28	83,000	75,250	67,500	61,000
29	83,000	75,000	67,000	60,500
30	83,000	74,750	66,500	59,750

PROGRAM:

III-$\overline{DG}$, Sym.	(.8, 1.2)	(.6, 1.4)	(.4, 1.6)	(.2, 1.8)
Population (10^7 pounds)	Effort Allocation (days)			
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
11	0	0	0	0
12	0	0	0	0
13	0	0	0	0
14	0	0	0	0
15	0	0	0	0
16	0	0	0	0
17	0	0	0	0
18	0	0	0	0
19	73,750	71,750	68,500	65,000
20	76,500	73,750	70,500	66,500
21	78,500	75,500	71,750	67,500
22	80,000	77,000	72,750	68,250
23	81,500	78,000	73,500	68,500
24	82,500	78,750	73,750	68,500
25	83,500	79,250	74,000	68,500
26	84,000	79,750	74,000	68,250
27	84,500	79,750	73,750	68,000
28	84,750	79,750	73,500	67,500
29	85,000	79,750	73,250	66,750
30	85,000	79,500	72,750	66,250

PROGRAM:

III-$\overline{DG}$, Skd.R. (.8, 1.5) (.8, 1.7) (.8, 1.9)

Population (10^7 pounds)	Effort Allocation (days)		
	(.8, 1.5)	(.8, 1.7)	(.8, 1.9)
0	0	0	0
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	0
10	0	0	0
11	0	0	0
12	0	0	0
13	0	0	0
14	0	0	0
15	0	0	0
16	0	0	0
17	0	0	0
18	0	0	0
19	71,250	69,500	67,500
20	73,500	71,250	68,500
21	75,000	72,500	69,500
22	76,250	73,250	70,250
23	77,250	74,000	70,250
24	77,750	74,250	70,000
25	78,250	74,250	69,500
26	78,500	74,000	69,250
27	78,500	73,750	68,250
28	78,500	73,250	67,000
29	78,000	72,500	66,000
30	77,750	71,750	64,750

PROGRAM:

III-$\overline{DG}$, Skd.L.	(.6, 1.2)	(.4, 1.2)	(.2, 1.2)
Population (10^7 pounds)	Effort Allocation (days)		
0	0	0	0
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	0
10	0	0	0
11	0	0	0
12	0	0	0
13	0	0	0
14	0	0	0
15	0	0	0
16	0	0	0
17	0	0	0
18	0	0	0
19	72,250	71,250	70,750
20	74,750	73,500	72,750
21	77,000	75,500	74,500
22	78,250	77,250	76,000
23	79,500	78,250	77,250
24	80,250	79,000	78,250
25	81,000	79,500	78,750
26	81,750	80,000	79,000
27	82,000	80,250	79,250
28	82,250	80,500	79,250
29	82,000	80,500	79,250
30	82,000	80,500	79,250

PROGRAM:

III-DG, Sym.U.	(.8, 1.2)	(.6, 1.4)	(.4, 1.6)	(.2, 1.8)
Population (10^7 pounds)	Effort Allocation (days)			
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
11	0	0	0	0
12	0	0	0	0
13	0	0	0	0
14	0	0	0	0
15	0	0	0	0
16	0	0	0	0
17	0	0	0	0
18	0	0	0	0
19	72,500	67,250	61,250	55,250
20	75,000	69,500	62,750	56,750
21	77,000	71,000	64,250	57,750
22	78,500	72,250	65,250	58,500
23	79,750	73,250	65,750	59,250
24	80,750	74,000	66,500	59,750
25	81,750	74,500	66,750	60,250
26	82,250	75,000	67,000	60,500
27	82,750	75,250	67,250	60,750
28	83,000	75,250	67,250	60,750
29	83,250	75,250	67,250	60,750
30	83,250	75,000	67,250	60,500

CLASS IV PROGRAMS

PROGRAM:

IV-P, Sym.U.	$ .15 x (.8, 1.2)	$.15 x (.6, 1.4)	$.15 x (.4, 1.6)	$.15 x (.2, 1.8)
Population (10^7 pounds)	Effort Allocation (days)			
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	250	250	250	250
11	1,500	2,000	2,500	3,750
12	12,500	12,500	12,500	12,500
13	12,000	12,000	12,250	12,500
14	20,500	20,500	20,500	20,500
15	23,000	23,000	23,000	22,750
16	25,750	25,750	25,750	25,750
17	27,500	27,250	27,000	26,500
18	29,500	29,500	29,500	29,250
19	34,000	34,000	33,250	32,500
20	32,500	32,250	31,750	31,750
21	35,500	35,500	35,500	35,000
22	35,500	35,000	34,500	33,500
23	36,250	36,250	36,250	36,250
24	39,000	39,000	39,000	39,000
25	39,750	39,250	38,750	37,750
26	39,000	39,000	39,000	39,000
27	41,000	41,000	41,000	40,250
28	42,250	41,500	40,500	39,000
29	40,750	40,250	40,250	40,250
30	41,750	41,750	41,750	41,750

PROGRAM:

IV-P, Sym.	\$.15 x (.8, 1.2)	\$.15 x (.6, 1.4)	\$.15 x (.4, 1.6)	\$.15 x (.2, 1.8)
Population (10^7 pounds)	Effort Allocation (days)			
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	250	250	250	250
11	1,500	1,500	1,750	2,750
12	12,500	12,500	12,500	12,500
13	12,000	12,000	12,000	12,250
14	20,500	20,500	20,500	20,500
15	23,000	23,000	23,000	23,000
16	25,750	25,750	23,750	25,750
17	27,500	27,250	27,250	27,000
18	29,500	29,500	29,500	29,500
19	34,000	34,000	33,750	33,500
20	32,750	32,250	32,250	31,750
21	35,500	35,500	35,500	35,500
22	35,500	35,250	35,000	34,500
23	36,250	36,250	36,250	36,250
24	39,000	39,000	39,000	39,000
25	39,750	39,500	39,250	38,750
26	39,000	39,000	39,000	39,000
27	41,000	41,000	41,000	41,000
28	42,250	42,000	41,500	40,500
29	40,750	40,500	40,250	40,250
30	41,750	41,750	41,750	41,750

PROGRAM:

IV-P, Skd.R.	\$.15 x (.8, 1.5)	\$.15 x (.8, 1.7)	\$.15 x (.8, 1.9)
Population (10^7 pounds)	Effort Allocation (days)		
0	0	0	0
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	0
10	250	250	250
11	1,500	1,500	2,000
12	12,500	12,500	12,500
13	12,000	12,000	12,000
14	20,500	20,500	20,500
15	23,000	23,000	23,000
16	25,750	25,750	25,750
17	27,250	27,250	27,250
18	29,500	29,500	29,500
19	34,000	34,000	34,000
20	32,500	32,250	32,250
21	35,500	35,500	35,500
22	35,250	35,250	35,000
23	36,250	36,250	36,250
24	39,000	39,000	39,000
25	39,500	39,500	39,500
26	39,000	39,000	39,000
27	41,000	41,000	41,000
28	42,000	41,750	41,500
29	40,500	40,250	40,250
30	41,750	41,750	41,750

PROGRAM:

IV-P, Skd.L.	\$.15 x (.6, 1.2)	\$.15 x (.4, 1.2)	\$.15 x (.2, 1.2)
Population (10^7 pounds)	Effort Allocation (days)		
0	0	0	0
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	0
10	250	250	250
11	1,500	1,500	1,500
12	12,500	12,500	12,500
13	12,000	12,000	12,000
14	20,500	20,500	20,500
15	23,000	23,000	23,000
16	25,750	25,750	25,750
17	27,250	27,250	27,250
18	29,000	29,500	29,500
19	34,000	34,000	34,000
20	32,500	32,500	32,250
21	35,500	35,500	35,500
22	35,500	35,250	35,000
23	36,250	36,250	36,250
24	39,000	39,000	39,000
25	39,750	39,500	39,250
26	39,000	39,000	39,000
27	41,000	41,000	41,000
28	42,000	41,750	41,500
29	40,740	40,750	40,250
30	41,750	41,750	41,750

PROGRAM:

IV-D, Sym.U.	(.8, 1.2)	(.6, 1.4)	(.4, 1.6)	(.2, 1.8)
Population (10^7 pounds)	Effort Allocation (days)			
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	250	250	250	250
11	1,750	3,250	5,250	7,250
12	11,250	10,500	10,500	11,750
13	14,000	15,500	15,250	15,250
14	19,000	18,750	19,250	18,750
15	22,250	22,000	22,000	21,500
16	25,000	24,750	24,250	24,000
17	27,750	27,250	26,750	26,250
18	30,000	29,250	28,500	27,750
19	31,500	31,000	30,750	29,750
20	33,500	32,750	32,000	31,000
21	35,000	34,250	33,250	32,000
22	36,000	35,500	34,250	33,250
23	37,000	36,500	35,500	33,500
24	38,250	37,500	36,250	34,750
25	39,250	38,250	37,000	35,250
26	39,750	39,250	37,750	36,250
27	40,250	39,750	38,500	36,250
28	40,750	40,000	38,750	37,000
29	41,250	40,250	39,000	37,000
30	41,500	40,750	39,250	37,250

PROGRAM:

IV-D, Sym.

Population (10^7 pounds)	(.8, 1.2)	(.6, 1.4)	(.4, 1.6)	(.2, 1.8)
	Effort Allocation (days)			
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	250
11	1,500	2,750	3,500	5,000
12	11,500	11,000	10,500	10,750
13	13,500	14,500	15,00	15,000
14	19,500	19,000	18,750	19,000
15	22,000	22,250	22,000	21,750
16	25,250	25,000	25,000	25,000
17	27,750	27,500	27,250	26,750
18	29,750	29,750	29,250	29,000
19	31,750	31,500	31,250	30,500
20	33,500	33,250	32,750	32,000
21	34,750	34,500	34,250	33,500
22	36,000	35,750	35,000	34,750
23	37,000	36,750	36,250	35,500
24	38,250	37,750	37,500	36,500
25	39,000	38,500	38,000	37,000
26	39,750	39,250	38,500	37,750
27	40,250	40,250	39,250	38,250
28	40,750	40,500	40,000	38,750
29	41,500	40,750	40,250	39,000
30	41,750	41,250	40,500	39,500

PROGRAM:

IV-D, Skd. R. (.8, 1.5) (.8, 1.7) (.8, 1.9)

Population (10^7 pounds)	Effort Allocation (days)		
	(.8, 1.5)	(.8, 1.7)	(.8, 1.9)
0	0	0	0
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	0
10	250	250	250
11	2,250	2,250	3,500
12	10,750	11,000	10,750
13	14,500	14,750	14,500
14	18,750	18,750	18,500
15	22,000	22,000	22,250
16	25,250	24,750	25,000
17	27,500	27,500	27.500
18	30,000	29,750	29,250
19	31,500	31,500	31,250
20	33,250	33,000	32,750
21	34,500	34,500	34,500
22	35,750	35,500	35,250
23	36,750	36,500	36,250
24	37,750	37,500	37,500
25	38,500	38,500	38,000
26	39,500	39,000	39,000
27	40,000	39,500	39,250
28	40,500	40,250	40,000
29	41,000	40,500	40,250
30	41,250	41,000	40,500

PROGRAM:

IV-D, Skd. L.	(.4, 1.2)	(.6, 1.2)	(.2, 1.2)
Population (10^7 pounds)	Effort Allocation (days)		
0	0	0	0
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	0
10	250	250	250
11	3,000	2,000	3,000
12	10,750	11,000	10,750
13	14,250	14,000	14,250
14	18,500	18,750	18,500
15	23,000	22,750	23,000
16	25,000	25,250	24,500
17	27,750	27,500	27,500
18	30,000	30,000	29,750
19	31,250	31,500	31,000
20	33,000	33,250	32,750
21	34,750	34,750	34,250
22	35,750	36,000	35,500
23	36,500	37,000	36,250
24	37,750	37,750	37,500
25	38,750	39,000	38,500
26	39,250	39,500	39,000
27	39,750	40,250	39,750
28	40,250	40,500	40,250
29	40,750	41,000	40,750
30	41,000	41,500	40,750

PROGRAM:

IV-$\overline{DG}$, Sym.U.	(.8, 1.2)	(.6, 1.4)	(.4, 1.6)	(.2, 1.8)
Population (10^7 pounds)	Effort Allocation (days)			
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	500
11	3,750	5,250	5,500	6,250
12	10,750	10,000	10,000	11,000
13	13,250	14,000	14,750	15,500
14	20,500	20,500	20,500	20,500
15	23,000	23,000	23,000	22,750
16	25,500	25,500	25,000	24,500
17	27,750	27,750	27,000	26,750
18	29,750	29,750	29,250	28,500
19	31,750	31,250	30,750	30,000
20	33,750	32,750	32,250	31,500
21	35,000	34,250	33,500	32,500
22	36,250	35,500	34,500	33,500
23	37,250	36,500	35,750	34,000
24	38,250	37,750	36,250	34,750
25	39,000	38,250	37,250	35,500
26	39,750	38,750	37,750	35,500
27	40,250	39,250	38,250	36,000
28	41,000	40,000	38,250	36,250
29	41,500	40,000	38,250	37,000
30	41,500	40,500	38,500	36,500

PROGRAM:

IV-$\overline{DG}$, Sym.

Population (10^7 pounds)	Effort Allocation (days) (.8, 1.2)	(.6, 1.4)	(.4, 1.6)	(.2, 1.8)
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
11	1,750	3,500	4,500	4,750
12	9,000	9,250	9,500	10,250
13	12,750	13,250	14,000	14,500
14	20,500	20,500	20,500	20,500
15	24,750	24,750	24,750	24,250
16	27,750	26,250	26,000	25,750
17	29,750	28,500	28,500	27,750
18	30,250	30,250	30,000	29,750
19	33,000	32,000	31,500	31,000
20	34,250	33,750	33,000	32,500
21	35,500	35,250	34,250	33,750
22	36,750	36,250	35,750	35,000
23	37,500	37,250	36,750	35,750
24	38,750	38,250	37,500	36,750
25	39,500	39,000	38,250	37,500
26	40,000	39,500	38,750	37,750
27	40,750	40,250	39,250	38,250
28	41,250	40,500	39,750	38,750
29	41,500	41,250	40,000	39,000
30	42,000	41,500	40,250	39,250

PROGRAM:

IV-$\overline{DG}$, Std. R. (.8, 1.5) (.8, 1.7) (.8, 1.9)

Population (10^7 pounds)	Effort Allocation (days)		
	(.8, 1.5)	(.8, 1.7)	(.8, 1.9)
0	0	0	0
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	0
10	0	0	0
11	4,500	4,750	4,750
12	10,250	10,500	10,500
13	13,500	14,000	14,250
14	20,500	20,500	20,500
15	23,000	23,000	23,000
16	25,750	26,000	26,000
17	27,500	27,250	27,000
18	30,250	30,250	30,000
19	31,500	31,000	31,000
20	33,500	33,500	33,250
21	34,500	34,250	33,750
22	36,250	35,750	35,750
23	36,750	36,500	36,250
24	38,000	37,500	37,500
25	38,500	38,250	38,000
26	39,500	39,250	39,000
27	40,000	39,500	39,250
28	40,250	40,250	39,750
29	40,750	40,500	40,250
30	41,250	40,750	40,500

PROGRAM:

IV-$\overline{DG}$, Skd. L.	(.6, 1.2)	(.4, 1.2)	(.2, 1.2)
Population (10^7 pounds)	Effort Allocation (days)		
0	0	0	0
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	0
10	0	0	0
11	4,000	4,250	4,000
12	10,750	10,750	10,750
13	13,500	13,500	13,500
14	20,500	20,500	20,500
15	23,000	23,000	23,000
16	25,250	25,000	25,000
17	28,000	28,250	28,250
18	29,750	29,250	28,750
19	31,750	31,500	31,250
20	34,000	34,000	33,750
21	34,500	34,500	34,500
22	35,750	35,750	35,500
23	37,250	37,000	36,750
24	38,000	37,750	37,250
25	38,750	38,250	38,000
26	39,500	39,250	39,000
27	40,000	39,750	39,500
28	40,750	40,250	40,250
29	41,250	40,750	40,500
30	41,750	41,000	40,750

PROGRAM:

IV-DG, Sym.U.	(.8, 1.2)	(.6, 1.4)	(.4, 1.6)	(.2, 1.8)
Population (10^7 pounds)	Effort Allocation (days)			
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
11	5,000	5,250	6,000	6,250
12	10,000	10,250	10,750	11,250
13	14,750	14,750	15,500	15,750
14	19,000	18,750	19,500	17,750
15	22,000	21,750	21m750	21,500
16	24,750	24,500	24,750	24,250
17	27,750	27,750	27,500	26,500
18	29,500	29,500	29,250	27,000
19	32,250	30,750	30,250	29,500
20	32,750	32,750	32,500	30,250
21	35,000	34,250	32,500	31,250
22	36,250	35,500	34,250	32,500
23	37,000	36,750	34,750	32,750
24	38,250	36,500	36,250	34,500
25	39,000	37,500	36,750	35,000
26	39,500	39,000	37,250	35,250
27	40,500	38,750	37,750	35,750
28	41,000	40,250	37,750	36,500
29	41,500	40,500	38,750	37,000
30	41,750	40,750	38,750	37,250

CLASS V PROGRAMS

PROGRAM:

V-P, Sym.U.	(.8, 1.2)	(.6, 1.4)	(.4, 1.6)	(.2, 1.8)
Population (10^7 pounds)	Effort Allocation (days)			
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	500	500	500	500
10	1,250	1,250	1,250	1,250
11	2,000	2,000	2,000	2,000
12	2,750	2,750	2,750	2,750
13	3,500	3,500	3,500	3,500
14	4,250	4,250	4,250	4,250
15	5,000	5,000	5,000	5,000
16	5,750	5,750	5,750	5,750
17	6,500	6,500	6,500	6,500
18	7,250	7,250	7,250	7,250
19	8,000	8,000	8,000	8,000
20	8,750	8,750	8,750	8,500
21	9,500	9,500	9,500	9,250
22	10,000	10,000	10,000	10,000
23	11,000	10,750	10,750	10,750
24	11,750	11,500	11,500	11,500
25	12,250	12,250	12,250	12,000
26	13,000	13,000	13,000	12,750
27	13,750	13,500	13,500	13,500
28	14,500	14,250	14,250	14,000
29	15,000	15,000	15,000	14,750
30	15,750	15,750	15,750	15,500

PROGRAM:

V-P, Sym.	(.8, 1.2)	(.6, 1.4)	(.4, 1.6)	(.2, 1.8)
Population (10^7 pounds)	Effort Allocation (days)			
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	500	500	500	500
10	1,250	1,250	1,250	1,250
11	2,000	2,000	2,000	2,000
12	2,750	2,750	2,750	2,750
13	3,500	3,500	3,500	3,500
14	4,250	4,250	4,250	4,250
15	5,000	5,000	5,000	5,000
16	5,750	5,750	5,750	5,750
17	6,500	6,500	6,500	6,500
18	7,250	7,250	7,250	7,250
19	8,000	8,000	8,000	8,000
20	8,750	8,750	8,750	8,750
21	9,500	9,500	9,500	9,500
22	10,000	10,000	10,000	10,000
23	11,000	11,000	10,750	10,750
24	11,750	11,750	11,500	11,500
25	12,250	12,250	12,250	12,250
26	13,000	13,000	13,000	13,000
27	13,750	13,750	13,500	13,500
28	14,500	14,500	14,250	14,250
29	15,000	15,000	14,750	14,750
30	15,750	15,750	15,500	15,500

PROGRAM:

V-P, Skd.R.	(.8, 1.5)	(.8, 1.7)	(.8, 1.9)
Population (10^7 pounds)	Effort Allocation (days)		
0	0	0	0
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	500	500	500
10	1,250	1,250	1,250
11	2,000	2,000	2,000
12	2,750	2,750	2,750
13	3,500	3,750	3,500
14	4,250	4,250	4,250
15	5,000	5,000	5,000
16	5,750	5,750	5,750
17	6,500	6,500	6,500
18	7,250	7,250	7,250
19	8,000	8,000	8,000
20	8,750	8,750	8,750
21	9,500	9,500	9,500
22	10,000	10,000	10,000
23	11,000	11,000	10,750
24	11,750	11,500	11,500
25	12,250	12,250	12,250
26	13,000	13,000	13,000
27	13,750	13,500	13,500
28	14,500	14,500	14,250
29	15,000	15,000	15,000
30	15,750	15,750	15,750

PROGRAM:

V-P, Skd.I.,	(.5, 1.2)	(.3, 1.2)	(.1, 1.2)
Population (10^7 pounds)	Effort Allocation (days)		
0	0	0	0
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	500	500	500
10	1,250	1,250	1,250
11	2,000	2,000	2,000
12	2,750	2,750	2,750
13	3,500	3,500	3,500
14	4,250	4,250	4,250
15	5,000	5,000	5,000
16	5,750	5,750	5,750
17	6,500	6,500	6,500
18	7,250	7,250	7,250
19	8,000	8,000	8,000
20	8,750	8,750	8,750
21	9,500	9,500	9,500
22	10,000	10,000	10,000
23	11,000	11,000	10,750
24	11,750	11,500	11,500
25	12,250	12,250	12,250
26	13,000	13,000	13,000
27	13,750	13,500	13,500
28	14,500	14,500	14,250
29	15,000	15,000	15,000
30	15,750	15,750	15,750

PROGRAM:

V-D, Sym.U.	(.8, 1.2)	(.6, 1.4)	(.4, 1.6)	(.2, 1.8)
Population (10^7 pounds)	Effort Allocation (days)			
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	500	500	500	500
10	1,250	1,250	1,250	1,250
11	2,000	2,000	2,000	2,000
12	2,750	2,750	2,750	2,750
13	3,500	3,500	3,500	3,500
14	4,250	4,250	4,250	4,250
15	5,000	5,000	5,000	5,000
16	5,750	5,750	5,750	5,750
17	6,500	6,500	6,500	6,500
18	7,250	7,250	7,250	7,250
19	8,000	8,000	8,000	8,000
20	8,750	8,750	8,750	8,750
21	9,500	9,500	9,250	9,250
22	10,250	10,250	10,000	10,000
23	10,750	10,750	10,750	10,750
24	11,500	11,500	11,500	11,500
25	12,250	12,250	12,250	12,000
26	13,000	13,000	13,000	12,750
27	13,750	13,750	13,500	13,500
28	14,250	14,250	14,250	14,000
29	15,000	15,000	14,750	14,750
30	15,750	15,750	15,500	15,250

PROGRAM:

V-D, Sym.	(.8, 1.2)	(.6, 1.4)	(.4, 1.6)	(.2, 1.8)
Population (10^7 pounds)	Effort Allocation (days)			
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	250	0	0	0
9	500	500	500	500
10	1,250	1,250	1,250	1,250
11	2,000	2,000	2,000	2,000
12	2,750	2,750	2,750	2,750
13	3,500	3,500	3,500	3,500
14	4,250	4,250	4,250	4,250
15	5,000	5,000	5,000	5,000
16	5,750	5,750	5,750	5,750
17	6,500	6,500	6,500	6,500
18	7,250	7,250	7,250	7,250
19	8,000	8,000	8,000	8,000
20	8,750	8,750	8,750	8,750
21	9,500	9,500	9,500	9,500
22	10,250	10,250	10,000	10,000
23	11,000	10,750	10,750	10,750
24	11,500	11,500	11,500	11,500
25	12,250	12,250	12,250	12,250
26	13,000	13,000	12,750	12,750
27	13,750	13,750	13,500	13,500
28	14,500	14,500	14,250	14,250
29	15,250	15,000	15,000	15,000
30	15,750	15,750	15,750	15,500

PROGRAM:

V-D, Skd. R.	(.8, 1.5)	(.8, 1.7)	(.8, 1.9)
Population (10^7 pounds)	Effort Allocation (days)		
0	0	0	0
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	500	500	500
10	1,250	1,250	1,250
11	2,000	2,000	2,000
12	2,750	2,750	2,750
13	3,500	3,500	3,500
14	4,250	4,250	4,250
15	5,000	5,000	5,000
16	5,750	5,750	5,750
17	6,500	6,500	6,500
18	7,250	7,250	7,250
19	8,000	8,000	8,000
20	8,750	8,750	8,750
21	9,500	9,500	9,500
22	10,250	10,000	10,250
23	10,750	10,750	10,750
24	11,500	11,500	11,500
25	12,250	12,250	12,250
26	13,000	13,000	13,000
27	13,750	13,750	13,750
28	14,250	14,250	14,250
29	15,000	15,000	15,000
30	15,750	15,750	15,500

PROGRAM:

V-D, Skd. I.	(.6, 1.2)	(.4, 1.2)	(.2, 1.2)
Population (10^7 pounds)	Effort Allocation (days)		
0	0	0	0
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	500	500	500
10	1,250	1,250	1,250
11	2,000	2,000	2,000
12	2,750	2,750	2,750
13	3,500	3,500	3,500
14	4,250	4,250	4,250
15	5,000	5,000	5,000
16	5,750	5,750	5,750
17	6,500	6,500	6,500
18	7,250	7,250	7,250
19	8,000	8,000	8,000
20	8,750	8,750	8,750
21	9,500	9,500	9,500
22	10,250	10,250	10,000
23	10,750	10,750	10,750
24	11,500	11,500	11,500
25	12,250	12,250	12,250
26	13,000	13,000	13,000
27	13,750	13,750	13,750
28	14,250	14,250	14,250
29	15,000	15,000	15,000
30	15,750	15,750	15,750

PROGRAM:

V-$\overline{DG}$, Sym.U.	(.8, 1.2)	(.6, 1.4)	(.4, 1.6)	(.2, 1.8)
Population (10^7 pounds)	Effort Allocation (days)			
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	500	750	750	750
10	1,250	1,250	1,250	1,500
11	2,000	2,000	2,000	2,250
12	3,000	2,750	3,000	2,750
13	3,500	3,500	3,500	3,750
14	4,250	4,250	4,250	4,250
15	5,000	5,000	5,000	5,000
16	5,750	5,750	5,750	5,750
17	6,500	6,500	6,500	6,500
18	7,250	7,250	7,250	7,250
19	8,000	8,000	8,000	8,000
20	8,750	8,750	8,750	8,750
21	9,500	9,500	9,500	9,250
22	10,000	10,000	10,000	10,000
23	11,000	10,750	10,750	10,750
24	11,500	11,500	11,500	11,500
25	12,250	12,250	12,250	12,000
26	13,000	13,000	12,750	12,750
27	13,750	13,500	13,500	13,500
28	14,250	14,250	14,250	14,000
29	15,000	15,000	14,750	14,750
30	15,750	15,500	15,500	15,250

PROGRAM:

Population (10^7 pounds)	Effort Allocation (days)			
V-$\overline{DG}$, Sym.	(.8, 1.2)	(.6, 1.4)	(.4, 1.6)	(.2, 1.8)
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	500	500	500	500
10	1,250	1,250	1,250	1,250
11	2,000	2,000	2,000	2,000
12	2,750	2,750	2,750	3,000
13	3,500	3,500	3,500	3,750
14	4,250	4,250	4,250	4,250
15	4,750	5,000	5,000	5,000
16	5,500	5,750	5,750	5,750
17	6,250	6,500	6,500	6,500
18	7,000	7,250	7,250	7,250
19	7,500	8,000	8,000	8,000
20	8,250	8,500	8,750	8,750
21	11,250	11,250	9,250	9,250
22	12,000	10,750	10,000	10,000
23	11,750	11,000	11,000	11,000
24	12,250	11,750	11,500	11,500
25	12,750	12,250	12,250	12,250
26	13,250	13,000	13,000	12,750
27	14,000	13,750	13,750	13,500
28	14,750	14,500	14,250	14,250
29	15,250	15,000	15,000	14,750
30	16,000	15,750	15,750	15,500

PROGRAM:

V-$\overline{DG}$, Skd. R.	(.8, 1.5)	(.8, 1.7)	(.8, 1.9)
Population (10^7 pounds)	Effort Allocation (days)		
0	0	0	0
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	500	500	500
10	1,250	1,250	1,250
11	2,000	2,000	2,000
12	2,750	2,750	2,750
13	3,500	3,500	3,500
14	4,250	4,250	4,250
15	5,000	5,000	5,000
16	5,750	5,750	5,750
17	6,500	6,500	6,500
18	7,250	7,250	7,250
19	8,000	8,000	8,000
20	8,750	8,750	8,750
21	9,500	9,500	9,500
22	10,000	10,000	10,000
23	11,000	11,000	11,000
24	11,500	11,500	11,500
25	12,250	12,250	12,250
26	13,000	13,000	13,000
27	13,750	13,750	13,750
28	14,250	14,250	14,250
29	15,000	15,000	15,000
30	15,750	15,750	15,750

PROGRAM:

V-$\overline{DG}$, Skd.L.	(.6, 1.2)	(.4, 1.2)	(.2, 1.2)
Population (10^7 pounds)	Effort Allocation (days)		
0	0	0	0
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	500	500	750
10	1,250	1,500	1,500
11	2,000	2,250	2,000
12	2,750	2,750	2,750
13	3,500	3,500	3,750
14	4,250	4,250	4,250
15	5,000	5,000	5,000
16	5,750	5,750	5,750
17	6,500	6,500	6,500
18	7,250	7,250	7,250
19	8,000	8,000	8,000
20	8,750	8,750	8,750
21	9,500	9,500	9,500
22	10,000	10,000	10,000
23	11,000	11,000	11,000
24	11,500	11,500	11,500
25	12,250	12,250	12,250
26	13,000	13,000	13,000
27	13,750	13,750	13,500
28	14,500	14,250	14,250
29	15,000	15,000	15,000
30	15,750	15,750	15,500

PROGRAM:

V-DG, Sym. U.	(.8, 1.2)	(.6, 1.4)	(.4, 1.6)	(.2, 1.8)
Population (10^7 pounds)	Effort Allocation (days)			
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	500	500	500	750
10	1,500	1,500	1,250	1,250
11	2,000	2,000	2,000	2,000
12	2,750	2,750	2,750	2,750
13	3,750	3,750	3,500	3,500
14	4,250	4,500	4,250	4,250
15	5,000	5,250	5,000	5,000
16	5,750	5,750	5,750	6,000
17	6,500	6,750	6,500	6,750
18	7,500	7,250	7,250	7,500
19	8,000	8,000	8,000	7,500
20	8,750	8,750	8,500	8,500
21	9,500	9,250	9,250	9,500
22	10,000	10,250	10,000	10,000
23	11,000	10,750	11,000	10,750
24	11,500	11,500	11,750	11,250
25	12,250	12,000	12,000	12,000
26	13,000	13,000	12,750	12,500
27	13,500	13,750	13,500	13,250
28	14,250	14,500	14,250	14,250
29	15,000	15,000	14,750	14,500
30	15,750	15,500	15,500	15,250

CLASS VI PROGRAMS

PROGRAM:

VI-P, Sym.U.	(.8, 1.2)	(.6, 1.4)	(.4, 1.6)	(.2, 1.8)
Population (10^7 pounds)	Effort Allocation (days)			
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
11	0	0	0	0
12	0	0	0	0
13	0	0	0	0
14	0	0	0	0
15	0	0	0	0
16	0	0	0	0
17	54,000	54,000	54,000	54,000
18	57,500	57,500	57,250	55,000
19	57,750	56,500	55,000	54,250
20	57,250	57,250	57,000	57,000
21	59,500	58,500	56,500	56,000
22	57,500	56,500	56,250	55,000
23	58,500	58,250	57,000	55,000
24	57,500	56,000	54,000	53,250
25	54,500	54,000	52,000	51,000
26	53,750	53,500	52,750	51,000
27	45,750	45,750	45,750	45,750
28	47,500	47,500	47,500	45,500
29	48,250	47,500	46,250	45,000
30	46,750	46,250	46,250	46,000

PROGRAM:

VI-P, Sym.	(.8, 1.2)	(.6, 1.4)	(.4, 1.6)	(.2, 1.8)
Population (10^7 pounds)	Effort Allocation (days)			
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
11	0	0	0	0
12	0	0	0	0
13	0	0	0	0
14	0	0	0	0
15	0	0	0	0
16	0	0	0	0
17	54,000	54,000	54,000	54,000
18	57,500	57,500	57,500	57,500
19	58,000	57,250	56,250	54,750
20	57,250	57,250	57,250	57,250
21	59,500	59,250	58,500	57,750
22	57,250	56,750	56,250	56,250
23	58,500	58,500	58,000	56,250
24	57,750	57,000	55,750	55,000
25	54,500	54,250	54,000	53,250
26	53,750	53,750	53,500	51,500
27	45,750	45,750	45,750	45,750
28	47,500	47,500	47,500	47,500
29	48,250	48,000	47,250	46,250
30	46,750	46,500	46,250	46,250

PROGRAM:

VI-P, Skd.R.	(.8, 1.5)	(.8, 1.7)	(.8, 1.9)
Population (10^7 pounds)	**Effort Allocation** (days)		
0	0	0	0
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	0
10	0	0	0
11	0	0	0
12	0	0	0
13	0	0	0
14	0	0	0
15	0	0	0
16	0	0	0
17	54,000	54,000	54,000
18	57,500	57,500	57,500
19	57,750	57,000	56,750
20	57,250	57,250	57,250
21	59,250	59,000	58,750
22	57,250	56,750	56,500
23	58,500	58,250	58,250
24	57,000	56,750	56,250
25	54,250	54,250	54,000
26	53,750	53,500	53,500
27	45,750	45,750	45,750
28	47,500	47,500	47,500
29	48,000	47,750	47,750
30	46,500	46,250	46,250

PROGRAM:

VI-P, Skd.L.	(.6, 1.2)	(.4, 1.2)	(.2, 1.2)
Population (10^7 pounds)	Effort Allocation (days)		
0	0	0	0
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	0
10	0	0	0
11	0	0	0
12	0	0	0
13	0	0	0
14	0	0	0
15	0	0	0
16	0	0	0
17	54,000	54,000	54,000
18	57,500	57,500	57,500
19	57,500	57,000	56,500
20	57,250	57,250	57,250
21	59,250	59,000	58,500
22	57,000	56,750	56,500
23	58,500	58,250	58,250
24	57,250	56,750	56,000
25	54,500	54,250	54,000
26	53,750	53,500	53,500
27	45,750	45,750	45,750
28	47,500	47,500	47,500
29	48,000	47,750	47,500
30	46,500	46,250	46,250

PROGRAM:

VI-D, Sym.U.	(.8, 1.2)	(.6, 1.4)	(.4, 1.6)	(.2, 1.8)
Population (10^7 pounds)	Effort Allocation (days)			
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
11	0	0	0	0
12	0	0	0	0
13	0	0	0	0
14	0	0	0	0
15	0	0	0	0
16	0	0	0	0
17	54,000	51,750	48,250	44,750
18	55,250	53,000	49,000	45,250
19	56,500	53,500	50,250	46,500
20	57,250	54,000	50,000	46,500
21	57,250	54,750	50,250	47,000
22	57,000	53,750	51,000	47,250
23	56,750	54,000	50,500	47,750
24	56,000	53,250	51,000	47,500
25	54,000	52,000	50,500	47,500
26	52,000	52,250	50,750	47,250
27	50,500	51,500	50,000	47,500
28	49,750	51,500	49,500	47,500
29	49,000	50,500	49,750	46,750
30	48,000	50,000	49,250	47,000

PROGRAM:

VI-D, Sym.	(.8, 1.2)	(.6, 1.4)	(.4, 1.6)	(.2, 1.8)
Population (10^7 pounds)	Effort Allocation (days)			
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
11	0	0	0	0
12	0	0	0	0
13	0	0	0	0
14	0	0	0	0
15	0	0	0	0
16	0	0	0	0
17	54,750	53,250	51,500	49,000
18	56,500	55,000	52,500	50,250
19	57,000	55,500	53,250	50,750
20	57,500	56,500	54,000	51,000
21	58,000	56,500	53,500	51,500
22	57,750	55,750	54,000	51,000
23	57,250	55,750	54,000	51,000
24	56,750	54,750	53,000	51,250
25	55,000	53,750	52,500	50,250
26	52,750	52,750	52,000	50,000
27	48,750	51,250	51,000	49,750
28	48,000	50,000	50,500	49,250
29	47,500	49,500	49,750	49,250
30	47,250	48,750	49,500	48,750

PROGRAM:

VI-D, Skd.R.	(.8, 1.5)	(.8, 1.7)	(.8, 1.9)
Population (10^7 pounds)	Effort Allocation (days)		
0	0	0	0
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	0
10	0	0	0
11	0	0	0
12	0	0	0
13	0	0	0
14	0	0	0
15	0	0	0
16	0	0	0
17	53,250	52,000	50,750
18	54,750	53,500	52,000
19	55,250	54,250	52,750
20	56,250	54,500	53,250
21	56,000	54,250	52,750
22	55,750	54,000	53,000
23	55,000	54,250	53,000
24	54,750	52,500	50,250
25	52,250	50,500	49,500
26	50,500	50,000	49,000
27	50,500	49,750	49,250
28	49,750	49,750	49,250
29	49,750	49,500	49,250
30	49,250	49,750	49,250

PROGRAM:

VI-D, Skd.L.	(.6, 1.2)	(.4, 1.2)	(.2, 1.2)
Population (10^7 pounds)	Effort Allocation (days)		
0	0	0	0
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	0
10	0	0	0
11	0	0	0
12	0	0	0
13	0	0	0
14	0	0	0
15	0	0	0
16	0	0	0
17	53,750	53,000	52,750
18	55,250	54,500	53,750
19	56,250	55,500	54,500
20	57,000	55,750	55,000
21	56,750	56,250	55,750
22	56,750	56,750	55,250
23	56,000	55,000	55,000
24	55,000	55,000	54,750
25	54,250	54,250	54,000
26	53,250	53,500	53,250
27	51,000	52,500	52,500
28	50,000	51,000	51,250
29	49,500	50,250	50,250
30	48,250	49,250	48,750

PROGRAM:

VI-$\overline{DG}$, Sym.U.	(.8, 1.2)	(.6, 1.4)	(.4, 1.6)	(.2, 1.8)
Population (10^7 pounds)	Effort Allocation (days)			
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
11	0	0	0	0
12	0	0	0	0
13	0	0	0	0
14	0	0	0	0
15	0	0	0	0
16	0	0	0	0
17	54,250	52,250	50,250	47,000
18	55,750	54,000	51,250	48,500
19	57,000	54,750	51,500	48,500
20	57,250	55,250	52,250	48,250
21	57,750	55,250	51,750	48,500
22	57,500	54,500	51,750	48,500
23	57,000	53,500	51,250	48,250
24	56,000	53,000	50,750	47,750
25	54,500	53,000	51,000	47,500
26	51,500	51,500	50,000	47,500
27	50,250	51,500	4[illegible],750	47,250
28	49,000	51,250	49,750	47,250
29	48,500	50,500	49,000	46,000
30	48,500	50,250	49,000	46,250

PROGRAM:

VI-$\overline{DG}$, Sym.	(.8, 1.2)	(.6, 1.4)	(.4, 1.6)	(.2, 1.8)
Population (10^7 pounds)	Effort Allocation (days)			
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
11	0	0	0	0
12	0	0	0	0
13	0	0	0	0
14	0	0	0	0
15	0	0	0	0
16	0	0	0	0
17	54,750	53,500	52,250	50,250
18	56,000	55,250	53,750	52,000
19	57,250	56,000	54,500	52,250
20	57,750	56,750	54,750	52,500
21	58,000	56,500	54,500	52,250
22	58,000	56,500	54,750	52,000
23	57,250	56,000	53,750	52,000
24	56,500	55,000	53,000	51,250
25	55,250	54,000	52,500	50,250
26	53,250	51,750	51,500	50,250
27	48,250	50,750	50,500	50,000
28	47,750	49,750	50,000	49,500
29	47,250	49,250	49,500	48,750
30	47,500	49,000	49,250	48,250

PROGRAM:

VI-DG, Skd.R.	(.8, 1.5)	(.8, 1.7)	(.8, 1.9)
Population (10^7 pounds)	Effort Allocation (days)		
0	0	0	0
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	0
10	0	0	0
11	0	0	0
12	0	0	0
13	0	0	0
14	0	0	0
15	0	0	0
16	0	0	0
17	53,750	53,000	52,250
18	55,000	54,250	53,750
19	55,750	55,000	54,000
20	56,500	55,000	54,500
21	56,750	55,000	54,750
22	56,750	55,000	54,250
23	55,750	54,750	53,250
24	55,000	53,750	51,500
25	52,250	50,250	49,500
26	50,250	49,750	49,250
27	49,750	49,750	49,000
28	49,750	49,250	49,250
29	49,500	49,250	49,250
30	49,000	49,500	49,250

PROGRAM:

VI-$\overline{DG}$, Skd.L.	(.6, 1.2)	(.4, 1.2)	(.2, 1.2)
Population (10^7 pounds)		Effort Allocation (days)	
0	0	0	0
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	0
10	0	0	0
11	0	0	0
12	0	0	0
13	0	0	0
14	0	0	0
15	0	0	0
16	0	0	0
17	54,250	54,000	53,250
18	55,000	55,000	54,500
19	56,000	55,000	55,000
20	57,250	56,500	56,000
21	57,500	56,750	55,750
22	57,000	56,500	55,500
23	56,250	56,250	55,750
24	55,000	55,000	55,000
25	54,000	54,250	54,000
26	52,500	52,750	53,000
27	51,000	52,000	52,500
28	50,000	51,750	51,500
29	48,750	49,500	50,500
30	48,500	49,000	48,250

PROGRAM:

VI-DG, Sym.U.	(.8, 1.2)	(.6, 1.4)	(.4, 1.6)	(.2, 1.8)
Population (10^7 pounds)	**Effort Allocation** (days)			
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
11	0	0	0	0
12	0	0	0	0
13	0	0	0	0
14	0	0	0	0
15	0	0	0	0
16	0	0	0	0
17	54,500	52,250	47,500	45,250
18	52,500	53,000	49,750	46,000
19	56,500	54,250	49,250	44,250
20	56,750	53,750	49,750	47,000
21	56,750	55,250	50,000	48,000
22	57,000	54,500	49,500	46,500
23	57,250	53,500	50,750	48,250
24	55,500	52,750	50,500	48,000
25	54,250	52,500	49,500	47,250
26	52,000	51,250	50,500	47,500
27	[illegible]0,250	51,250	50,250	46,250
28	50,250	51,250	49,500	47,500
29	49,250	50,250	49,000	47,000
30	48,500	49,750	48,500	46,750

GROWTH VARIATION PROGRAMS

PROGRAM:

Population (10^7 pounds)	I (.2, 1.8)	II (.2, 1.8)	III (.2, 1.8)
	Effort Allocation (days)		
0	0	0	0
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	500	0
10	0	1,250	0
11	0	2,000	0
12	0	2,750	0
13	8,750	3,500	0
14	17,500	4,250	0
15	25,000	5,000	0
16	31,250	5,750	0
17	36,500	6,500	0
18	41,250	7,250	0
19	45,250	8,000	72,750
20	48,750	8,750	75,750
21	52,000	9,500	78,000
22	54,750	10,250	80,000
23	57,000	11,000	81,500
24	58,750	11,750	83,000
25	60,500	12,250	84,250
26	61,750	13,000	85,000
27	63,000	13,750	85,750
28	64,750	14,500	86,750
29	66,250	15,250	88,000
30	67,250	16,000	88,500

GROWTH VARIATION PROGRAMS

PROGRAM:

Population (10^7 pounds)	IV (.2, 1.8)	V (.2, 1.8)	VI (.2, 1.8)
	Effort Allocation (days)		
0	0	0	0
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	500	0
10	0	1,250	0
11	5,000	2,000	0
12	9,750	2,750	0
13	15,000	3,500	0
14	18,500	4,250	0
15	22,250	5,000	0
16	25,250	5,750	0
17	27,250	6,500	53,750
18	29,750	7,250	55,500
19	31,750	8,000	57,000
20	33,500	8,750	57,500
21	34,750	9,500	57,750
22	36,250	10,250	58,000
23	37,250	10,750	58,000
24	38,250	11,500	57,750
25	39,000	12,250	57,250
26	40,000	13,000	57,000
27	40,500	13,750	46,000
28	41,250	14,500	46,750
29	40,750	15,000	47,000
30	41,750	15,750	46,250

Footnotes

[1] An important example where price fluctuations are quite large and are believed to have a significant impact on resource allocation occurs in the Peruvian Anchovy Fishery; see Segura (1972).

[2] Unfortunately, the problem of insufficient data is not peculiar to the yellowfin tuna fishery. To my knowledge, at the present time there is little available information to estimate these frequency distributions for any of the ocean fisheries.

[3] For example, Leland (1974), Levhari and Srinivasan (1966), and Phelps (1962) in their analyses of optimal consumption-saving rules discover that individuals with a constant elasticity utility function given by

$$U(C) = \begin{cases} \dfrac{C^{\gamma}}{\gamma} & \text{for } \gamma < 1;\ \gamma \neq 0 \\ \log(C) & \text{for } \gamma = 0 . \end{cases}$$

will increase, decrease or not change their consumption of total wealth for $0 < \gamma < 1$, $\gamma < 0$ or $\gamma = 0$ as the rate of return on investment becomes riskier. In other studies, Mills (1959) and Zabel (1970) have noted the strong dependence of results on stochastic specifications assumed in their models.

[4] Please note that the scale for effort on the vertical axis of all graphs corresponding to Classes II and V is enlarged. Also, the effort allocations for all programs are identical for those populations where only one line appears on the graph.

[5] In equilibrium $(a-bX)X = kXE$ or $E = \frac{(a-bX)}{K}$. Equilibrium values for E are represented by points on the "Steady State Effort" line in each figure.

[6] See Rothschild and Stiglitz (1970).

[7] This is partially offset by the fact that the utility function $U(R) = \ln(R+G)$ displays decreasing absolute risk aversion. Thus as R increases the resource manager should become less averse to risk.

[8] For a discussion of this point see Hirshleifer and Shapiro (1970).

[9] On this point see Baumol (1970, and Hirshleifer and Shapiro (1970).

[10] See Prest and Turvey (1965).

[11] Leland's analysis is done in the context of a portfolio-consumption framework.

[12] Although the absolute increase in present value is large for Class I programs, the percentage increase is less than 1%. However for the Class III programs the percentage increases range from 1% to 30%.

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