# A BIOECONOMIC MODEL FOR DETERMINING THE OPTIMAL TIMING OF HARVEST FOR THE NORTH CAROLINA BAY SCALLOP FISHERY

By

Robert L. Kellogg, J. E. Easley Jr. and Thomas Johnson

Department of Economics and Business

North Carolina State University

Raleigh, North Carolina

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# CHAPTER 1. INTRODUCTION

The role for state regulation of fisheries arises from the common property/open access nature of the resource. Without property rights, individual fishermen ignore the value of the productive capacity of the stock (also called the opportunity cost of harvesting). Instead, fishermen attempt to harvest as much as they can as fast as they can when expected net return is positive. Under these conditions, serious depletion of the resource can occur. The task facing the fishery manager is the promulgation of regulations designed to ensure continued harvests and, if possible, to enhance the value of those harvests. The fishery manager must also be concerned about the trade-off between gains from regulation and the costs of regulation (such as enforcement costs, information costs and administrative costs). Most importantly, the fishery manager does not want to promulgate regulations that are inconsistent with optimal harvest strategies.

Bioeconomic models and optimal control theory can be used by fishery managers to help attain these goals. With a specified objective to be optimized (such as maximizing net revenue) and a specified control variable, or regulatory device (such as the season opening date), optimal control theory can be used to solve for the optimal harvest of the resource over time. The procedure requires that both the biological and economic aspects of the fishery be incorporated into a bioeconomic model. Important components include the objective function, the price function, the fish production function, the cost function, and functions describing the population dynamics of the resource stock. Regulations that are based on the solution of the optimal control problem will preserve stock for continued harvests, provide incentives for fishermen to harvest rationally, and improve the overall value of the harvest. By comparing results for the unregulated case with results for the optimal solution, the manager can get an estimate of the economic gains from regulation. This information is invaluable for deciding if regulations are cost effective.

The fisheries management problem is a problem in capital theory, which was defined by Dorfman (1969) as "the economics of time." The fish population can be viewed as a capital stock that, like "conventional" or man-made capital, is capable of yielding a consumption flow through time. The management problem thus becomes one of selecting an optimal consumption path, or harvest path, through time (Clark and Munro 1975). Optimal control theory is used to solve for this optimal path. In fact, Dorfman (1969) has shown that optimal control theory is formally identical to capital theory by deriving the principal theorem of optimal control theory—called the maximum principle—by means of economic analysis. There are a number of recent works where theoretical optimal control models are advanced (for example, Clark 1976; Huang et al. 1976; Strand and Hueth 1977; Clark and Munro 1980; Levhari et al. 1981; and Conrad and Castro 1983), but few examples of applications to specific fishery problems.

The purposes of this paper are 1) to present a general harvesting model that can be used to address the problem of when to open and close the harvest season for a seasonal (intermittent) fishery, 2) to apply the model to the North Carolina bay scallop fishery and 3) to incorporate uncertainty into the manager's decision process using simulation and stochastic dominance rules.

The seasonal fisheries model is presented in Chapter 2 and applied to the bay scallop fishery in North Carolina in Chapter 3. In Chapter 4, stochastic dominance rules are applied to the bay scallop harvesting problem as an example of how economic decision theory can enhance the use of optimal control models.

# CHAPTER 2. A DYNAMIC SEASONAL HARVESTING MODEL

## 2.1 The General Model

A seasonal fishery can be defined as one in which there are naturally occuring intraseasonal variations in yields. For these fisheries, economic inefficiency might result from harvesting the fish too early in the year. In the common property/open access situation, individual fishermen are motivated to harvest seasonal fisheries early—when stocks are high and before they are depleted by other fishermen—even though the value of the catch may be much greater later in the season (Agnello and Donnelley 1977). The seasonal harvesting model presented in this section can be solved for the <u>optimal</u> season-opening (and season-closing) schedule such that net revenue for the fishery is maximized.

The general fisheries management model for a seasonal fishery can be formally stated as follows:

maximize with respect to $\Phi(t)$

$$PV = \int_0^{\infty} [P(Q,t,w)Q(x,t,y) - C(x,t,y)] e^{-\delta t} \Phi(t)\, dt.$$

such that

$$\dot{x} = F(x,t,z) - M(x,t,z) - Q(x,t,y)\,\Phi(t),$$
$$x(t_0) \text{ and } t_0 \text{ given,}$$

where $\Phi(t)$ = the control variable ( $\Phi(t)=0$ implies a closed season and $\Phi(t)=1$ implies an open season),

$P(Q,t,w)$ = the fish price function,

$Q(x,t,y)$ = the fish production function, (fishing mortality),

$C(x,t,y)$ = the cost function,

$e^{-\delta t}$ = the discount function,

$F(x,t,z)$ = the population growth function,

$M(x,t,z)$ = the natural mortality function,

$w$ = vector of exogenous variables affecting market price,

$z$ = vector of exogenous environmental variables,

$y$ = vector of exogenous production inputs,

$x(t)$ = population size in numbers,

$t$ = time.

Feasibility constraints and conditions on functions may be desirable for some problems. For instance, politically infeasible solution sets can sometimes be incorporated into the problem in the form of constraints on the state variables. (See Kamien and Schwartz (1981) for details regarding necessary and sufficient conditions, endpoint conditions and other conditions needed for unique solutions.) The model can be extended by including stochastic elements. Stochasticity is important, but rigorous treatment of stochasticity in applications is secondary to refinement of the biological and economic models.

This general model has been formulated with continuous time and an infinite time horizon. Discrete optimal control models can also be formulated (Johnson 1985; Clark 1976), as well as finite terminal time problems. The essential difference between use of finite terminal time and an infinite time horizon is that the infinite time horizon leads typically to an optimal steady state, or long-run equilibrium solution. Fisheries with strong stock-recruitment relationships are best modelled with an infinite time horizon, whereas fish populations that fluctuate in abundance from year to year independent of harvest activities—predominantly because of changes in habitat availability or environmental conditions—can often be modelled effectively with a finite time horizon (where the time interval is a single harvest season).

The model is applicable primarily for single year class fisheries, but it could be used for multi-cohort fisheries in special cases. The indicator function would serve as a "pulse fishing" control (see Clark 1976, page 174, for a discussion of this type of control variable). However, seasonal control over the harvest period alone would probably not be the control mechanism most suited for multi-cohort fisheries, since growth rates and user costs would probably vary among the cohorts. Regulations on cohort-specific harvest rates--perhaps in conjunction with season closings--would be generally more appropriate for multi-cohort fisheries (see optimal harvest recommendations of Conrad (1982) and correction by Hsiao (1985)).

### 2.1.1 The Objective Functional

The objective functional is the part of the problem that is to be maximized by selection of an "optimal" control vector. It contains most of the economic aspects of the problem. In the above model, the objective is to manipulate the control variable so as to maximize the discounted value of net revenue. The objective functional is

$$\int_0^\infty [P(Q,t,w)Q(x,t,y)-C(x,t,y)]e^{-\delta t}\,\Phi(t)\,dt.$$

In words, this represents the sum over all future time periods of the net revenue (total revenue minus cost) from harvest of the fishery resource denominated in current dollars (i.e., the present value).

Ideally, the objective function would represent the sum over all future time periods of the net benefits to society from the production and consumption of the fishery resource. Benefits would measure the aggregate subjective values placed on fish consumption by each member of society in common units of measure. Costs of production would be measured according to the value of alternative uses of the inputs (opportunity costs). With costs and benefits defined in this way, the maximizing solution would be optimal to society as a whole (maximum social welfare). There may be "winners" and "losers" resulting from regulation, but if regulation is justified, the losses would be outweighed by the gains.

But this idealistic approach is not possible in practice for two basic reasons. First, benefits and costs are inherently subjective and cannot be observed directly. Second, even if they could be observed and measured, the most that can be obtained is an ordinal measure (an ordering of preferences), whereas a cardinal measure is required to trade off benefits and costs among producers and consumers. Consequently, the theoretical objective (in terms of social welfare) must be replaced by a less suitable--but more operational--objective. The most common approach in fisheries problems (and the one used in this study) is to substitute net revenue for society's net benefit function. (Maximizing net revenue is equivalent to maximizing producer surplus when the price function is infinitely elastic.)

Of course, net revenue is not a perfect measure of social value because it assumes that the marginal utility of money is the same for all individuals in society and at all points in time. The value of an extra fish to a poor man is taken to be the same as the value to a rich man. Thus, the model is insensitive to income redistribution. To be responsive to allocational issues related to regulation, it would be desirable to incorporate income distribution features into the objective function. Incorporation of social and political objectives is also desirable (Crutchfield 1972; Bishop et al. 1981; Waugh 1984). The more "realistic" the objective function is, the more useful the results. Although extension of the objective function to include these important factors is theoretically possible, it is difficult to do in practice. To date, little work has been done in this area in application to specific fishery problems.

### 2.1.2 The Price Function

The price function (an inverse demand function), P(Q,t,w), describes the market price of the fishery product. It is typically in units of dollars per pound. It is usually modelled as a function of both quantity and time, of time only, or as a constant. In addition, exogenous variables such as personal income and prices of substitutes might be included.

The most common form of the price function in fisheries problems is infinitely elastic, that is, the fishermen and the regulating authority are price takers. This occurs when the quantity produced within the jurisdiction of the managing authority is small relative to the total harvest, and thus changes in local harvests have little or no impact on price. (Only the population within the jurisdiction of the managing authority is modelled in the optimal control problem.) When price is a function of quantity, it may be desirable to substitute another objective function in place of discounted net revenue because consumer surplus is not included in the net revenue calculation.

### 2.1.3 The Production Function

The production function, $Q(x,t,y)$, specifies the rate of output of a process over time in terms of its inputs. A typical fisheries production function would include the fish stock and fishing effort inputs (vessel size and number, crew size and skill, etc., usually represented by a single index labelled "effort"). A common representation of the production function in the fisheries literature is the harvest rate, $h(t)$. In this form, the harvest rate also serves as the control variable, where it is assumed that the social manager has complete control over production. It is also popular to represent the harvest rate as a production function with two inputs, effort ($E(t)$) and the fish stock ($x$), as follows:

$$Q(x,t,y) = h(t) = qE(t)x(t),$$

where q is a "catchability" coefficient and is needed to transform $E(t)$ (measured in nominal terms, such as number of vessels or number of fishermen) into a fishing mortality rate. This is sometimes referred to as the "catch per unit effort hypothesis" (Clark 1976). $E(t)q$ represents fishing mortality, since it is the proportion of the population size represented by the catch. Although this production function is popular in fisheries work, there are some important assumptions associated with its use: non-saturation of fishing gear, no congestion of fishing vessels, and uniform distribution of the stock (needed to guarantee a constant q).

A more general functional form for the production function is $\phi(x)\,\Psi(E)$, where $\Psi(E)$ defines the effect of fishing effort on a stock (the mortality rate), and $\phi$ defines the total fishing mortality generated by $\Psi$ acting on x. This general form of the production function is discussed by Clark (1976) and Hannesson (1983). Relating this functional form to the catch per unit effort hypothesis, $\Psi(E)=qE(t)$ and $\phi(x)=x(t)$. Fishing effort is taken here to be a composite index of inputs consisting of fishing skills, size of vessels, crew size, fuel, etc. Alternatively, this index can be disaggregated into its constituent parts. These variables can then be modelled either as exogenous variables or, if regulated by the managing authority, included as controls.

### 2.1.4 The Cost Function

The cost function, $C(x,t,y)$, defines the total costs of producing, or harvesting, the fish. It is often represented in terms of cost per fish harvested, $C(x)$. The harvest rate, $h(t)$, is then multiplied times the cost per fish harvested to obtain total costs:

$$C(x,t,y) = C(x)h(t).$$

An alternative representation of costs is cost per unit of effort, $C(E)$, which is then multiplied by fishing effort to obtain total costs:

$$C(x,t,y) = C(E)E(t).$$

The first representation is frequently used in theoretical work whereas the second is used more in empirical studies (including the present study).

Ideally, the cost function would measure the <u>opportunity costs</u> of inputs, and not just the accounting costs. For fuel, food and other inputs that can easily be put to use in other segments of the population, the market price is a good estimate of the opportunity cost. But measuring the opportunity cost of labor and of the highly specialized gear often used in fisheries is difficult. The opportunity cost of fishermen is the social value of what their labor would produce in its next-best alternative use. The incomes received from fishing are usually not a good measure of opportunity cost, but are, instead, the amount necessary to keep them working (Anderson 1977). Moreover, opportunity costs vary considerably from fisherman to fisherman and even from week to week.

### 2.1.5 The Discounting Function

A discounting function, $e^{-\delta t}$, is required in the objective functional because benefits from the fishery are being added up over time by the integration process, and they must be in common units of value for the sum to be legitimate. The most general form of the discounting function is

$$e^{-\int_{s}^{t} \delta(s)ds},$$

where s is the dummy variable of integration and $\delta$ is the instantaneous discount rate. (If t is in units of years, then $\delta$ is an annual discount rate.) In this form, the discount rate is allowed to vary over time.

This form is never used in applications, however, because 1) the manner in which $\delta(t)$ changes over time is not known, and 2) the problem becomes difficult mathematically when $\delta$ is other than a constant. Consequently, the discounting function used is typically $e^{-\delta t}$.

An increase in the discount rate leads to a faster depletion of exhaustible resources, and a decrease leads to a slower depletion. The choice of an appropriate value for $\delta$ is the subject of controversy

(Mendelsohn 1981). Whose discount rate should be used? The fisherman's? The banker's? A social rate of time preference? The problem is that all of the consumers and producers involved have different opportunity costs of investment (some are lenders and some are borrowers, for example). Determining one value to represent all of society is difficult. The value chosen for $\delta$ is very important for infinite time horizon problems, but it is less important when the time horizon is less than a year.

2.1.6 Equations of Motion

The equations of motion, $\dot{x}$, comprise the biological sector of the fisheries management model. The equations of motion define how the state variables, $x(t)$, move through time. In a fisheries problem, the state variables usually define the population dynamics of the species or cohorts involved. At least one equation of motion for each state variable is required. When several state variables are present, the equations of motion are represented by a system of differential equations. An "initial condition" is needed for each equation of motion in order to solve the system of differential equations.

The equations of motion represent constraints on the availability of the resource; hence, they are often referred to as ''resource constraints.'' A renewable resource (such as a fishery) cannot instantly replace the stock that is harvested. It takes time to replenish the population. This process usually depends on the absolute stock size, water quality variables, habitat availability, food availability, predators and other factors. If modelled fully, the equations of motion more aptly could be called "ecosystem constraints," since they represent how the ecosystem (or rather, a subset of the ecosystem) would respond to a prescribed harvest rate of one or more of the species involved.

The presence of the population growth function, $F(x,t,z)$, in the equations of motion is what designates the resource as a "renewable" resource. In general, growth functions are nonlinear and cyclical when spawning and recruitment occur during a particular time of the year.

Inclusion of water temperature in the growth function is especially important. Fish are cold-blooded, and thus their growth and metabolic rates are determined predominantly by water temperature. For this reason, Bell (1972) and O'Rourke (1971) included temperature in their population equations, and Hall (1977) extended the Schaeffer yield model to include temperature. Loucks and Sutcliffe (1978) observed correlations between ocean temperatures, subsequent catch of cod and yellowtail flounder, and fishing effort. Sissenwine (1974) demonstrated that variability in catch statistics of the yellowtail flounder fishery correlated well with three and four year moving averages of atmospheric temperature. Fishery models that ignore the effects of temperature and/or other environmental influences will never enjoy ''good fits'' when estimated. Note also that constantly changing environmental influences—such as temperature--preclude the establishment of an equilibrium state, at least in the sense of obtaining sustained yields.

The natural mortality function, $M(x,t,z)$, is theoretically a function of population size, water quality variables, the abundance of predators and time. Because of data constraints, however, natural mortality functions used in practice are usually much simpler. Mortality from fishing activity is simply the fish production function, $Q(x,t,y)$.

## 2.2 A Modified Model for Single Year Class Fisheries

The model can be simplified by restricting it to represent single year class fisheries where the stock-recruitment relationship (embodied in F, the population growth function) is either fully protected by regulations that prohibit harvesting during the spawning season or where the stock-recruitment relationship is overwhelmed by environmental factors. The preponderance of single year class fisheries falls into one or the other of these two groups. This simplification affects the seasonal harvesting model by changing the infinite time horizon to a finite time horizon, equal to the potential or natural season length. The finite time horizon is indicated by $t=T$ in the model.

Additional simplification can be obtained by defining x to be in terms of numbers of fish rather than in biomass units (pounds). This does not alter any of the fundamental characteristics of the model, but permits the model to be expressed in a simpler form. The price variable must be in units of dollars per fish, rather than in dollars per pound. This is accomplished by multiplying $P(Q,t,w)$ (in units of dollars per pound) by a size function for individuals in the population (in units of pounds per fish). This size function is designated as $g(z,t)$ and is theoretically a function of environmental variables (especially water temperature) and time.

The population growth function, $F(x,t,z)$, must also be in units of number of fish. Since the stock-recruitment relationship has been assumed away, this function consequently reduces to a function of z and t only-- $F(z,t)$. Knife-edge recruitment (when individuals become available to the fishery all at the same time) is modelled by setting $F(z,t)$ equal to zero for $t>0$ and equal to the initial population size at $t=0$. A non-zero $F(z,t)$ for $t>0$ represents a recruitment pattern over time.

The control model is now in the form of a model for an exhaustible resource. The state variable, x (the number of fish), cannot increase during the time horizon of the control problem except according to a prescribed recruitment pattern. It can decrease either by natural mortality, $M(x,t,z)$, or fishing mortality, $Q(x,t,y)$. Incorporating these simplifications into the general model, the seasonal harvesting model for single year class fisheries is formally presented as:

maximize with respect to $\Phi(t)$

$$PV = \int_0^T [P(Q,t,w)g(z,t)Q(x,t,y)-C(x,t,y)]e^{-\delta t}\,\Phi(t)\,dt.$$

such that

$$\dot{x} = F(z,t) - M(x,t,z) - Q(x,t,y)\,\Phi(t).$$

$$x(t_0) \text{ and } t_0 \text{ given, } 0 \leq t \leq T.$$

It is assumed that the decision regarding when to begin harvest is made prior to the potential harvest season and that, once made, it is irrevocable. That is, the possibility of adaptive management is ignored. In actual practice, however, the season opening/closing schedule could be re-assessed at any time if important additional information is acquired.

The above model can be applied to multiple species when more than one species is vulnerable to capture by the harvesting operation. For example, several species of shrimp can be included, each with a different state variable, size function, etc. Predator and prey species can be included as well. Catch of incidental (non-target) species, which usually have little or no direct commercial value at the time of collection but which may have commercial value at a later date, can be included in the problem by adding the appropriate equations of motion and assigning value to the "bycatch" on the basis of its eventual commercial value. (See Waters et al. (1980) and Waters (1983) for an example of an economic analysis of the foregone value of bycatch of immature shrimp in relation to proposed restrictions on the timing of harvest.)

## 2.3 General Method for Solving the Seasonal Harvesting Model

The seasonal harvesting model developed in the last section can be written in general terms by suppressing all exogenous variables and combining functions such as market price, size, etc., as follows:

$$\underset{\Phi(t)}{\text{maximize with respect to}} \quad PV = \int_0^T I(t,x(t))\,\Phi(t)\,dt$$

$$\text{such that} \quad \dot{x} = f(x(t),t) - Q(x,t,y)\,\Phi(t)$$

$$x(0) \text{ given, } x(t) \geq 0.$$

Relating these terms to expressions used in Section 2.2, we have

$$I(t,x(t)) = [P(Q,t,w)g(x,t)Q(x,t,y) - C(x,t,y)]e^{-\delta t},$$

and

$$f(x(t),t) = F(x,t) - M(x,t,z).$$

The terminal time, T, is the absolute time limit for the problem, representing the natural end of the season. Since only single year class fisheries are involved, T can be thought of as the time when any remaining stock "disappears." Fishing would cease prior to time T because of unprofitability.

The maximum principle technique is used to solve this problem (Clark 1976; Intriligator 1971; Kamien and Schwartz 1981). The maximum principle says that the optimal control can be obtained by maximizing a function called the "Hamiltonian" at each moment over the time horizon of the problem. Here, the Hamiltonian function is defined as

$$H(t,x(t),\lambda(t),\Phi(t)) = I(t,x(t))\ \Phi(t) + \lambda(t)\{f(x(t),t)-Q(x,t,y)\ \Phi(t)\}.$$

$\lambda(t)$ is a vector of adjoint, or co-state variables. There is an adjoint variable for each state variable in the problem. Since the objective functional is in terms of net revenue and the state variable is a quantity, each adjoint variable has the dimension of a price, which is called the "shadow" price of the state variable (Intriligator 1971). The shadow price is the monetary value of changes in the state variable. In other words, it is the value of an additional unit of x and thus is a measure of the productive value of the stock. It is also called the marginal user cost. It is called a "shadow" price because it is an implicit cost; the manager does not actually pay it. Given this economic interpretation of $\lambda(t)$, it is clear that $\lambda(t)\geq 0$ and $\lambda(T)=0$ in order for the Hamiltonian to be maximized.

There is also an economic interpretation of the Hamiltonian. The Hamiltonian at time t is the net revenue at time t (the net value of the catch) plus the value of the changes in the state variables at time t (the productive value of the stock). In other words, the Hamiltonian represents the total rate of increase of total assets, which in turn is equal to the value of accumulated dividends (the first term) plus the value of changes in capital assets (the second term) (Clark 1976: p.104). Note that in order to maximize the Hamiltonian, the decision maker must know the value of $\lambda$ at each moment during the time interval. Furthermore, the value of the Hamiltonian at T must equal zero. Otherwise, it would not be optimal to stop fishing at T, which is required by the problem formulation. Of course, the Hamiltonian can also equal zero at any time prior to T.

The solution is found by solving for $\Phi(t)$, $\lambda(t)$, and $x(t)$ that satisfy the following necessary conditions:

1) $\underset{\Phi(t)}{\text{maximize with respect to}}\quad H(t,x(t),\lambda(t),\Phi(t))$ for each t in (0,T)

2) $\dot{x} = \partial H/\partial\lambda = f(x(t),t)-Q(x,t,y)\ \Phi(t)$, $\quad x(0) = x_0$, and

3) $\dot{\lambda} = -\partial H/\partial x = -(\partial I/\partial x)\ \Phi(t) - \{\partial f/\partial x - \Phi(t)\partial Q/\partial x\}\lambda(t)$, $\lambda(t)\geq 0$.

4) $\lambda(T) = 0$ and $H(T)=0$.

Since the Hamiltonian is linear in the control variable, the first condition--maximizing the Hamiltonian--can be met by simply setting $\Phi=0$ or $\Phi=1$ depending on whether the Hamiltonian is positive ( $\Phi=1$) or negative ( $\Phi=0$). Such a solution is known as a bang-bang control. This condition can be expressed using a switching function:

$$\Phi(t) = \begin{cases} 1 & \text{if } I(t,x(t)) - \lambda(t)\{f(x(t),t)-Q(x,t,y)\} > 0 \\ 0 & \text{if } I(t,x(t)) - \lambda(t)\{f(x(t),t)-Q(x,t,y)\} \leq 0. \end{cases}$$

The switching function depends on $x(t)$ and $\lambda(t)$, which are obtained by solving the differential equations, and on the exogenous variables that determine the catch rate and costs. In general, this will mean solving a system of 2n simultaneous equations, where n is the number of state variables.

The above necessary conditions are not sufficient conditions, however. If $\Phi$ is switched to zero before time T (which would usually be the case), the problem becomes a free end time problem. With a fixed end time problem, the terminal, or transversality, conditions are the boundary condtitions for $\lambda$. With a free end time problem, iterative techniques are required. Values for $\lambda$ at time zero are selected until the one resulting in the optimum present value is found. These necessary conditions do provide that once the appropriate $\lambda(0)$ is determined, the solution of $\Phi(t)$ will be the optimal solution.

# CHAPTER 3. APPLICATION OF THE SEASONAL HARVESTING MODEL TO THE NORTH CAROLINA BAY SCALLOP FISHERY

## 3.1 Description of the Fishery

The bay scallop fishery in North Carolina is an annual winter fishery, traditionally opening in December and extending through early spring. Bay scallops spawn in their first year and most do not survive to spawn a second year. Harvesting is prohibited during the spawning period in the fall to ensure continued harvests in subsequent years. The state regulatory agency (North Carolina Department of Natural Resources and Community Development, Division of Marine Fisheries) controls the season opening. Other controls include quotas, restrictions on the days during the week when harvesting is allowed, closure of the commercial fishery on weekends, restriction of fishing to daylight hours, and certain gear restrictions designed to prevent destruction of the habitat. Catch limits and the opening dates for harvest seasons since 1968-1969 are summarized in Table 1. Prior to 1969 there were no catch limits; catch limits were imposed only after widespread use of the scallop drag resulted in increased harvest rates, which sometimes exceeded the processing capacity (Dennis Spitsbergen, Division of Marine Fisheries, personal communication).

The fishery is predominantly a small-boat fishery (under 25 feet) because bay scallops live in shallow water. Bay scallops are harvested primarily by use of a scallop drag (dredge or scrape). This device consists of a frame about a yard wide with a retainer bag of two-inch bar mesh netting. Scallopers pull from one to four drags behind a motorized boat, with the most common number being two. Scallop drags were prohibited from 1935 to 1965. During that time fishermen used scoops or rakes to collect scallops. Today these methods are usually limited to areas inaccessible by boat or to periods of low tide. Use of scallop drags with teeth or drags weighing greater than 50 pounds is prohibited to prevent destruction of the sea grass beds.

Traditionally, fishing has been allowed only on two to three days per week during the first two months of the season. As the season progresses, allowed fishing days may be increased to five days per week. Commercial fishing for scallops is not permitted on Saturdays and Sundays. Scalloping for private consumption (recreational fishing) is allowed on weekends during the open season if harvested by non-mechanical means (rakes, dip nets or by hand) and the catch is limited to one-half bushel per fisherman with a maximum of one bushel per boat.

Bay scallops harvested in North Carolina are processed in the local community. Scallops may be shucked by the fishermen themselves, or the shucking may be contracted to a local fish house (processing plant) and the meats sold by the fisherman to the wholesaler, or the shell stock may be sold directly by the fishermen to a local fish house. All scallop processors, including fishermen who shuck their own scallops, must comply with regulations of the North Carolina Department of Health, Shellfish Sanitation Section, which establishes a permit system for the shucking, handling and packaging of scallops. Fricke (1981) reported that in 1977 approximately 28

Table 1. Catch statistics and summary of regulations on season openings and catch limits for the bay scallop fishery in North Carolina from 1969-1983. (Data from the National Marine Fisheries Service and the North Carolina Division of Marine Fisheries.)

| Year | Total landings for the harvest season[a] (pounds) | Total ex-vessel value for the harvest season (dollars) | Date of season opening | Catch limit[b] |
|---|---|---|---|---|
| 1968-69 | 692,290 | 415,000 | Dec 2 | None |
| 1969-70 | 154,783 | 110,000 | Dec 1 | 20 |
| 1970-71 | 32,972 | 20,000 | Nov 30 | 20 |
| 1971-72 | 184,652 | 150,000 | Dec 6 | None |
| 1972-73 | 848 | 1,272 | Dec 11 | None |
| 1973-74 | 229,600 | 210,000 | Dec 3 | 20 |
| 1974-75 | 117,888 | 93,708 | Dec 2 | 40(20) |
| 1975-76 | 273,572 | 192,427 | Dec 1 | 40(20) |
| 1976-77 | 225,012 | 473,661 | Dec 6 | 40(20) |
| 1977-78 | 269,708 | 458,227 | Dec 5 | 40(20) |
| 1978-79 | 130,928 | 299,040 | Jan 15 | 20(10) |
| 1979-80 | 306,319 | 1,073,006 | Dec 3 | 40(20) |
| 1980-81 | 226,479 | 817,396 | Dec 8 | 15 |
| 1981-82 | 128,111 | 268,985 | Nov 30 | 15 |
| 1982-83 | 161,327 | 494,964 | Nov 29 | 15 |

[a]Includes the December catch from the previous calendar year, so values are actual catches for each harvest season. Units are in pounds of meats.
[b]The catch limit is in bushels per boat per day. In some years, an additional limit of bushels per day per fisherman was imposed (shown in parentheses).

percent of the bay scallop harvest was sold as fresh scallops to restaurants in Carteret County, while the remainder (72 percent) was quick-frozen, canned or cooked before sale.

In good years, the bay scallop fishery has provided seasonal employment for 3,000 to 5,000 persons and contributed as much as a tenth of the income of a full-time fisherman (Fricke 1981). In addition to full-time fishermen, many individuals who have full-time jobs outside the fishing industry harvest scallops during annual leave or seasonal unemployment periods. Season landings of bay scallops from North Carolina waters have varied considerably, ranging from less than 1,000 pounds (meat weight) to nearly 700,000 pounds since 1969 (Table 1). Landings have been typically in the 100,000-pound to 300,000-pound range. Although the bay scallop fishery in North Carolina is important locally, it usually constitutes less than one percent of the annual scallop yield in the United States, and an even smaller percentage of the total supply of scallops when imports are considered.

## 3.2 <u>The Model</u>

The general seasonal harvesting model presented in the previous chapter was adapted for application to the North Carolina bay scallop fishery. The equation of motion was simplified to include only the harvest rate. Since there is no recruitment in terms of numbers during the potential harvest season, $F(x,t)$ is zero. Natural mortality during the potential harvest season, $M(x,t,z)$, was assumed to be zero as well. Additionally, it is postulated that the production function can be represented by the catch-per-unit-effort production function, and that the cost function can be represented by a cost-per-unit-effort function. Incorporating these modifications into the problem results in the following model for bay scallops:

maximize with respect to $\Phi(t)$

$$PV = \int_0^T [P(Q,t,w)g(z,t)E(t)qx(t)-cE]e^{-\delta t} \quad (t)\ dt.$$

such that

$$\dot{x} = -E(t)qx(t)\ \Phi(t)$$

$$x(0) \text{ given, } 0 \le t \le T, \text{ and } x(t) \ge 0,$$

where $P(Q,t,w)$ = the market price equation in dollars per pound,

$Q$ = quantity (pounds) of the North Carolina bay scallop catch,

$w$ = vector of exogenous variables in the market price equation,

$z$ = vector of exogenous environmental variables,

$g(z,t)$ = the scallop size equation in pounds per scallop,

$E(t)q$ = fishing mortality,

$c$ = cost per unit of effort,

$x(t)$ = population size in numbers,

$t$ = time in units of weeks starting from December 1, and

$\Phi(t)$ = the decision variable ( $\Phi(t)=0$ implies a closed season and $\Phi(t)=1$ implies an open season).

The potential harvest season is defined to span from December 1 ($t=0$) to March 31 ($t=T$). $E(t)$ is a standard measure of fishing effort and $q$ is the catchability coefficient for the designated unit of effort. The weekly discount rate, $\delta$, was set equal to 0.001827 for this study, which is equivalent to an annual discount rate of 10 percent. This is a real rate (that is, the rate after adjusting for inflation). A real rate is required here because price and cost are in units of uninflated dollars (1967 dollars).

Each of the components of the harvesting model (such as the market price equation, the size equation, etc.) will be discussed in detail in the next section. The calculation of the optimal harvest season will then be presented in Section 3.4 and research needs will be discussed in Section 3.5.

## 3.3 Components of the Model

### 3.3.1 Ex-vessel Price Equation

There are three species of scallops harvested in the United States—bay scallops, sea scallops and calico scallops. Sea scallops are harvested in the northeast Atlantic Ocean by U.S. and Canadian fishermen and constitute the bulk of the total scallop supply. Calico scallops are harvested primarily off the coast of Florida. Bay scallops are harvested primarily in North Carolina, New York, Massachusetts and Rhode Island. Bay scallops represent less than 7 percent (since 1976) of the U.S. scallop supply. The meats of the three species have nearly the same properties except for size; sea scallops tend to be larger than bay scallops and calico scallops.

The extent to which the market place discriminates among the three species is not clear. The three species are probably close substitutes for some uses and perfect substitutes for other uses. Highest national prices occur for bay scallops and lowest for calico scallops (South Atlantic Marine Fisheries Council (1981: Table 9-4). (In North Carolina, however, higher ex-vessel prices are observed for sea scallops than for bay scallops.) Ex-vessel prices of scallops of all species in North Carolina tend to be lower than the national average. These price differences are probably due to differences in processing costs and transportation costs rather than differences in consumer preference. Most scallops are frozen and stored for transportation to inland markets or for later consumption. This creates an inventory demand in addition to consumption demand. Furthermore, local demand for fresh scallops may also be an important factor.

Thus, the demand for bay scallops is a complex interplay of both consumption and inventory demand, supply of all three scallop species, and local (seasonal) demand for the fresh product. It is beyond the scope of this study to model this demand system fully. Instead, a single-equation model for North Carolina ex-vessel price was developed and estimated. (The equation can alternatively be viewed as a reduced-form equation with no supply shifters.) Because sea scallops dominate the scallop market, the price of bay scallops would be expected to be determined to a large degree by factors that are important in the sea scallop market.

The demand equation is postulated as follows:

$$NCQ_t = f(INCOME_t, NCP_t, SEAP_t, SEAP^e_{t+1}, INVENT_t, PSHRIMP_t, CALQ_t, TIME),$$

where $NCQ_t$ is the demand quantity of North Carolina bay scallops in pounds of meats (unprocessed), $NCP_t$ is the ex-vessel price of North Carolina bay scallops in dollars per pound of meats, $SEAP_t$ is the current period ex-vessel price of sea scallops, $SEAP^e_{t+1}$ is the expected future ex-vessel price of sea scallops. $INVENT_t$ is the inventory of frozen stocks of scallops at the beginning of the period t, $PSHRIMP_t$ is the ex-vessel price of shrimp, $CALQ_t$ is the landings of calico scallops, and TIME represents a group of variables that account for temporal shifts in demand during the harvest season. $SEAP_t$ and $PSHRIMP_t$ represent prices of substitutes, and together with $INCOME_t$ and $NCP_t$ comprise the standard variables expected in a demand equation. TIME is included to capture seasonal changes in demand, which can be important for products that are available on a strictly seasonal basis. For example, local demand for fresh scallops may be high when the season first opens, but may taper off later in the season. TIME would also capture seasonal changes in demand that result from increasing size of the meat as the season progresses, assuming that the consumers exhibit a size preference. $SEAP^e_{t+1}$ and $INVENT_t$ represent the inventory demand response in the sea scallop market. The demand for inventories depends, among other factors, on the expected future prices and the current level of inventory. For example, a higher expected price for next period might lead to increased buying in the current period and a resulting increase in the inventory stock. The $CALQ_t$ variable is included as a demand shifter because high calico scallop landings have sometimes been observed to depress the North Carolina bay scallop market when the harvests coincided (Dennis Spitsbergen, Division of Marine Fisheries, personal communication). Calico scallops were landed from North Carolina beds in 1978 and 1981, and trucked from Florida for processing in North Carolina in 1981 and 1982 when the Florida processing sector could not handle the volume of scallops harvested.

Prior to estimation, this equation was formulated as a linear equation and transformed to an inverse demand equation by solving for NCP. To be consistent with the time unit used in other aspects of the scallop harvesting model, TIME was defined in terms of weeks starting from December 1:

$$TIME = \gamma_1 WEEK + \gamma_2 WEEK^2 + \gamma_3 WEEK^3.$$

The PSHRIMP variable was re-defined as a shrimp price index (published by the U.S. Department of Commerce in "Current Fisheries Statistics"). The index is a Laspeyres-type price index with 1967 as the base year. All prices and income were adjusted for inflation prior to the estimation by dividing by the consumer price index; thus, all prices are in units of 1967 dollars. The final modification was a replacement of $SEAP^e_{t+1}$ by a 3-period distributed lag model, where

$$SEAP^e_{t+1} \cong \beta_1 SEAP_t + \beta_2 SEAP_{t-1} + \beta_3 SEAP_{t-2}.$$

The resulting price equation is as follows:

$$NCP_t = a_0 + a_1 INCOME_t + a_2 NCQ_t + a_3 SEAP_t + a_4 SEAP_{t-1} + a_5 SEAP_{t-2}$$
$$+ a_6 PSHRIMP_t + a_7 CALQ_t + a_8 WEEK + a_9 WEEK^2 + a_{10} WEEK^3 + a_{11} INVENT_t$$

Monthly data on prices, quantities and income were used to fit this model. The data and their sources are presented in Kellogg (1985), Appendix A. The models were estimated using data from 1974-1975 through 1982-1983. Only data for the potential harvest season—December through March--were used in fitting the model. Since the price equation requires time in units of weeks, the midpoint of each month, measured in weeks, was used (that is, WEEK = 2.2, 6.6, 10.9 and 15.0 for December, January, February and March, respectively).

The results of fitting the price equation are shown in Table 2. The $R^2$ was 0.708. The three TIME variables—WEEK, $WEEK^2$, and $WEEK^3$--were tested as a group for significance and were found to be statistically significant ($\alpha$=0.05) ($F_{3,23}$=3.637). The two lagged sea scallop prices were similarly tested together and also found to be significant ($F_{2,23}$=7.583). The significant coefficient for CALQ reinforces the Division of Marine Fisheries's perception that the erratic catches of calico scallops influenced the price of bay scallops in North Carolina. (It should be noted that if the calico scallop harvest becomes more regular, the importance of CALQ in the price equation would diminish, necessitating a re-estimation of the equation.) The variables $NCQ_t$, $PSHRIMP_t$ and $INVENT_t$ had non-significant t-ratios and remained non-significant when tested jointly, ($F_{3,23}$=0.308). The lack of importance of the North Carolina harvest ($NCQ_t$) in determining the ex-vessel price in North Carolina is not surprising in view of the small proportion of the total scallop supply represented by the North Carolina harvest. This result suggests that management actions and regulations, while they may affect income and yields, will not affect the price of bay scallops.

In applications, each of the independent variables will need to be forecasted in order to use the above equation to predict future prices. It is therefore important that only the most relevant variables be included.

Table 2. Statistical results from estimating the full model for ex-vessel price of North Carolina bay scallops.

MODEL:

$$NCP_t = a_0 + a_1 INCOME_t + a_2 NCQ_t + a_3 SEAP_t + a_4 SEAP_{t-1} + a_5 SEAP_{t-2}$$
$$+ a_6 PSHRIMP_t + a_7 CALQ_t + a_8 WEEK + a_9 WEEK^2 + a_{10} WEEK^3 + a_{11} INVENT_t.$$

| SOURCE | DF | SUM OF SQUARES | MEAN SQUARE | F-VALUE |
|---|---|---|---|---|
| MODEL | 11 | 3.54716445 | 0.32246950 | 5.06 |
| ERROR | 23 | 1.46592456 | 0.06373585 | |
| CORRECTED TOTAL | 34 | 5.01308901 | | (PR>F= 0.0005) |

$R^2$ = 0.70758 ROOT MSE = 0.25245960

| VARIABLE | PARAMETER ESTIMATE | T FOR H0: PARAMETER=0 | PR > \|T\| | STD ERROR OF ESTIMATE |
|---|---|---|---|---|
| INTERCEPT | -3.62847863 | -2.21 | 0.0375 | 1.64382944 |
| $INCOME_t$ | 0.00379481 | 1.41 | 0.1720 | 0.00269188 |
| $NCQ_t$ | 1.1354418E-06 | 0.61 | 0.5454 | 0.00000185 |
| $SEAP_t$ | -1.97299849 | -3.14 | 0.0046 | 0.62789450 |
| $SEAP_{t-1}$ | 0.68808097 | 1.15 | 0.2632 | 0.59989948 |
| $SEAP_{t-2}$ | 1.77670043 | 2.90 | 0.0082 | 0.61348777 |
| $PSHRIMP_t$ | -0.05640425 | -0.32 | 0.7523 | 0.17662204 |
| $CALQ_t$ | -5.7657525E-07 | -3.42 | 0.0024 | 0.00000017 |
| WEEK | 0.34991078 | 1.75 | 0.0934 | 0.19991462 |
| $WEEK^2$ | -0.03577499 | -1.32 | 0.2006 | 0.02714856 |
| $WEEK^3$ | 0.00098686 | 0.95 | 0.3536 | 0.00104226 |
| INVENT | 2.7650218E-08 | 0.47 | 0.6426 | 0.00000006 |

The market price prediction equation used in subsequent analyses was determined by dropping the non-significant variables--$NCQ_t$, $PSHRIMP_t$ and $INVENT_t$--from the model. Parameter estimates for this reduced model are presented in Table 3.

In practice, the equation in Table 3 will be used to predict prices for the potential harvest season (December-March). It will thus be necessary to forecast values for sea scallop price, calico scallop landings and income. It is also important that the combination of these variables be near or within the sample space used to estimate the parameters of the equation. It is possible to use reasonable values for each of the exogenous variables and get poor price predictions simply because the combination of variables was not represented in the original dataset. Statistics for each of the exogenous variables used in the estimation is given below as a guide:

| VARIABLE | N | MEAN | STANDARD DEVIATION | MINIMUM VALUE | MAXIMUM VALUE |
|---|---|---|---|---|---|
| $INCOME_t$ | 36 | 856.5 | 46.740 | 763.0 | 910.0 |
| $SEAP_t$ | 36 | 1.44 | 0.332 | 0.932 | 2.088 |
| $SEAP_{t-1}$ | 36 | 1.44 | 0.329 | 0.966 | 2.088 |
| $SEAP_{t-2}$ | 36 | 1.44 | 0.318 | 0.966 | 2.088 |
| $CALQ_t$ | 36 | 347902 | 363016 | 0 | 1253255 |

For the present study, the season averages of these variables for two harvest seasons (1980-1981 and 1981-1982) were used:

| Variable | 1980-81 | 1981-82 |
|---|---|---|
| $INCOME_t$ | 882 | 887 |
| $SEAP_t=SEAP_{t-1}=SEAP_{t-2}$ | 2.00 | 1.31 |
| $CALQ_t$ | 531,369 | 1,084,457 |

The 1980-1981 set of values produced a relatively high price path, whereas the 1981-1982 set produced a relatively low price path.

### 3.3.2 Scallop Size Equation

The scallop size equation, g(z,t), was developed previously by Kellogg and Spitsbergen (1983). The growth rate of the scallop meat was modelled as a function of meat size and the growth rate of the shell, which were in turn determined by water temperature. The basic model was a Brody-Bertalanffy growth equation with a temperature dependent growth coefficient, as follows:

Table 3. Statistical results from estimating the reduced model for ex-vessel price of North Carolina bay scallops. This price equation was used in the scallop harvesting problem.

MODEL:

$$NCP_t = a_0 + a_1 INCOME_t + a_3 SEAP_t + a_4 SEAP_{t-1} + a_5 SEAP_{t-2}$$
$$+ a_7 CALQ_t + a_8 WEEK + a_9 WEEK^2 + a_{10} WEEK^3.$$

| SOURCE | DF | SUM OF SQUARES | MEAN SQUARE | F-VALUE |
|---|---|---|---|---|
| MODEL | 8 | 3.48834848 | 0.43604356 | 7.44 |
| ERROR | 26 | 1.52474053 | 0.05864387 | |
| CORRECTED TOTAL | 34 | 5.01308901 | | (PR>F=0.0001) |

$R^2 = 0.695848$ ROOT MSE = 0.24216496

| VARIABLE | PARAMETER ESTIMATE | T FOR H0: PARAMETER=0 | PR > \|T\| | STD ERROR OF ESTIMATE |
|---|---|---|---|---|
| INTERCEPT | -4.24904127 | -4.50 | 0.0001 | 0.94400997 |
| $INCOME_t$ | 0.00473008 | 3.96 | 0.0005 | 0.00119327 |
| $SEAP_t$ | -1.85448147 | -3.38 | 0.0023 | 0.54878495 |
| $SEAP_{t-1}$ | 0.56224238 | 1.02 | 0.3167 | 0.55072151 |
| $SEAP_{t-2}$ | 1.69072116 | 2.96 | 0.0065 | 0.57155936 |
| $CALQ_t$ | -5.4761407E-07 | -4.15 | 0.0003 | 0.00000013 |
| WEEK | 0.38661194 | 2.19 | 0.0378 | 0.17668992 |
| $WEEK^2$ | -0.04133764 | -1.74 | 0.0944 | 0.02380936 |
| $WEEK^3$ | 0.00119521 | 1.31 | 0.2003 | 0.00090949 |

$$M_t = M_{max}(1-e^{-B(C,t)}) + M_0 e^{-B(C,t)},$$

where $B(C,t) = b_1 t + b_2 C + b_3 C^2/t,$

$M_t$ = meat size in grams at time t,

$M_{max}$ = maximum attainable meat size,

$M_0$ = initial meat size at t=0 (November 1),

t = time in weeks from November 1, and

C = cumulative water temperature in degrees centigrade (degree-weeks) from November 1 to time t.

(The scallop size equation developed by Kellogg and Spitsbergen (1983) has a different starting time than the harvesting model, necessitating a modification of the size equation, which is discussed later.)

The model was refined further by substituting an expression for the maximum size that the meat can attain, $M_{max}$:

$$M_{max} = m_1 S_t^{m_2},$$

where $S_t$ is the length of the shell. This is the same general relationship used commonly in fisheries to relate weight to length. Shell size was then also modelled as a function of cumulative temperature in the same manner as the meat model. The shell growth model is

$$S_t = S_{max}(1-e^{-B_S(C,t)}) + S_0 e^{-B_S(C,t)}$$

where $B_S(C,t) = c_1 t + c_2 C + c_3 C^2/t,$

$S_t$ = shell length in centimeters at time t,

$S_{max}$ = maximum attainable shell size, and

$S_0$ = initial shell length at t=0 (a variable).

The growth function, $B_S(C,t)$, is the same form as that used in the meat model except that the parameters have different values.

Using the above models, scallop meat size can be predicted for any week in the potential harvest season. The shell size equation is used to predict $S_t$, and then that value is substituted into the meat size equation. Information needed to estimate the size equation includes an initial measure (or estimate) of shell size on about November 1 and projections of cumulative water temperature. In application, the initial value for shell size can be estimated by sampling, and an expected water temperature curve could be constructed on the basis of regional long-term weather predictions and temperatures prevalent prior to the season.

Kellogg and Spitsbergen (1983) estimated coefficients for these two models. Parameter estimates for the meat and shell size models are as follows (Kellogg and Spitsbergen 1983: Tables 5 and 6):

| | | | |
|---|---|---|---|
| $M_0$ = | 2.522 | $S_{max}$ = | 6.378 |
| $b_1$ = | −0.4415 | $c_1$ = | −0.0298 |
| $b_2$ = | 0.0969 | $c_2$ = | 0.0065 |
| $b_3$ = | −0.0034 | $c_3$ = | 0 |
| $m_1$ = | 0.0270 | | |
| $m_2$ = | 3 | | |

In addition, the variable $S_0$ was set equal to 5.9 centimeters, which is the average shell size for the month of November (Kellogg and Spitsbergen 1983: Table 3).

The remaining information needed to calculate meat size is cumulative water temperature. Using a seven-year database, Kellogg and Spitsbergen (1983) estimated water temperature (degrees Centigrade) for the Beaufort Channel as a quadratic in time over the potential harvest season. An equation for cumulative water temperature (in degree-weeks) was subsequently obtained by integrating the original equation with respect to time. The resulting equation for "normal" cumulative water temperature is:

$$C = 20.203t - 1.012t^2 + 0.027t^3,$$

where C is cumulative temperature in degree-weeks from November 1 and t is time in weeks from November 1. (The original equation estimated by Kellogg and Spitsbergen (1983) included dummy variables for warm and cold winters. These were set equal to zero here to produce the equation for a "normal" winter. Whereas the temperature regime during unusually cold or warm winters can influence the optimal season opening/closing schedule, only the average, or normal, temperature regime will be considered in this study.)

There are two unit changes that are necessary before the scallop size equation can be compatable with the seasonal harvesting model. First, meat size is predicted in grams, whereas the harvesting model requires meat size in pounds. Thus, the meat size equation was multiplied by 0.002205 to convert grams to pounds. Second, the time unit for the meat size equation is weeks starting from November 1, whereas the seasonal harvesting model requires time in weeks from December 1. This was reconciled by replacing t with t+4.3 (4.3 is the number of weeks in November) for every t in the size equation. Consequently t=0 would correspond to December 1 and t=17.3 to March 31, as required. The resulting size equation is shown in Figure 1. The price-per-scallop function, obtained by multiplying the size equation (pounds per scallop) by the ex-vessel price equation (price per pound) is shown in Figure 2.

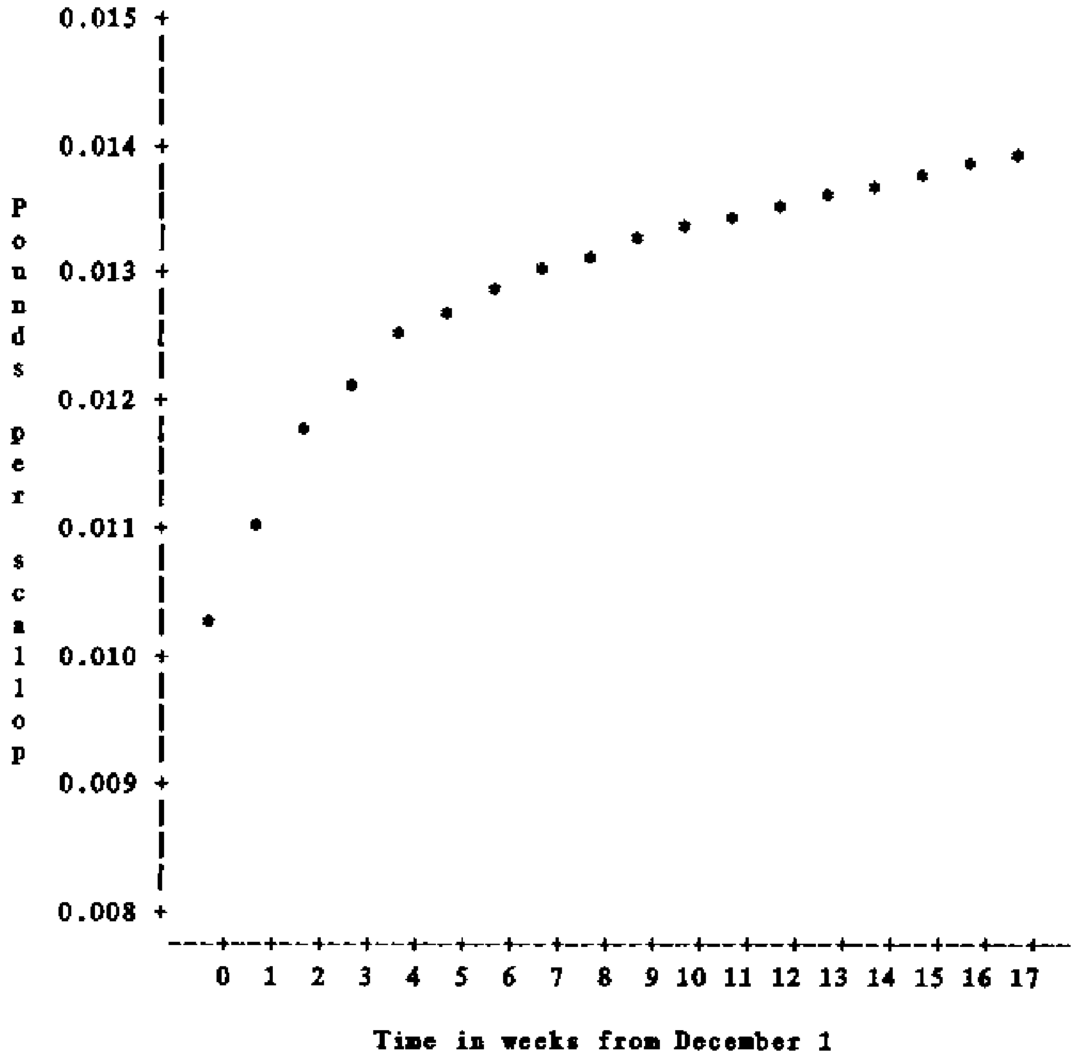


Figure 1. The bay scallop meat size function, g(z,t), in pounds per scallop.

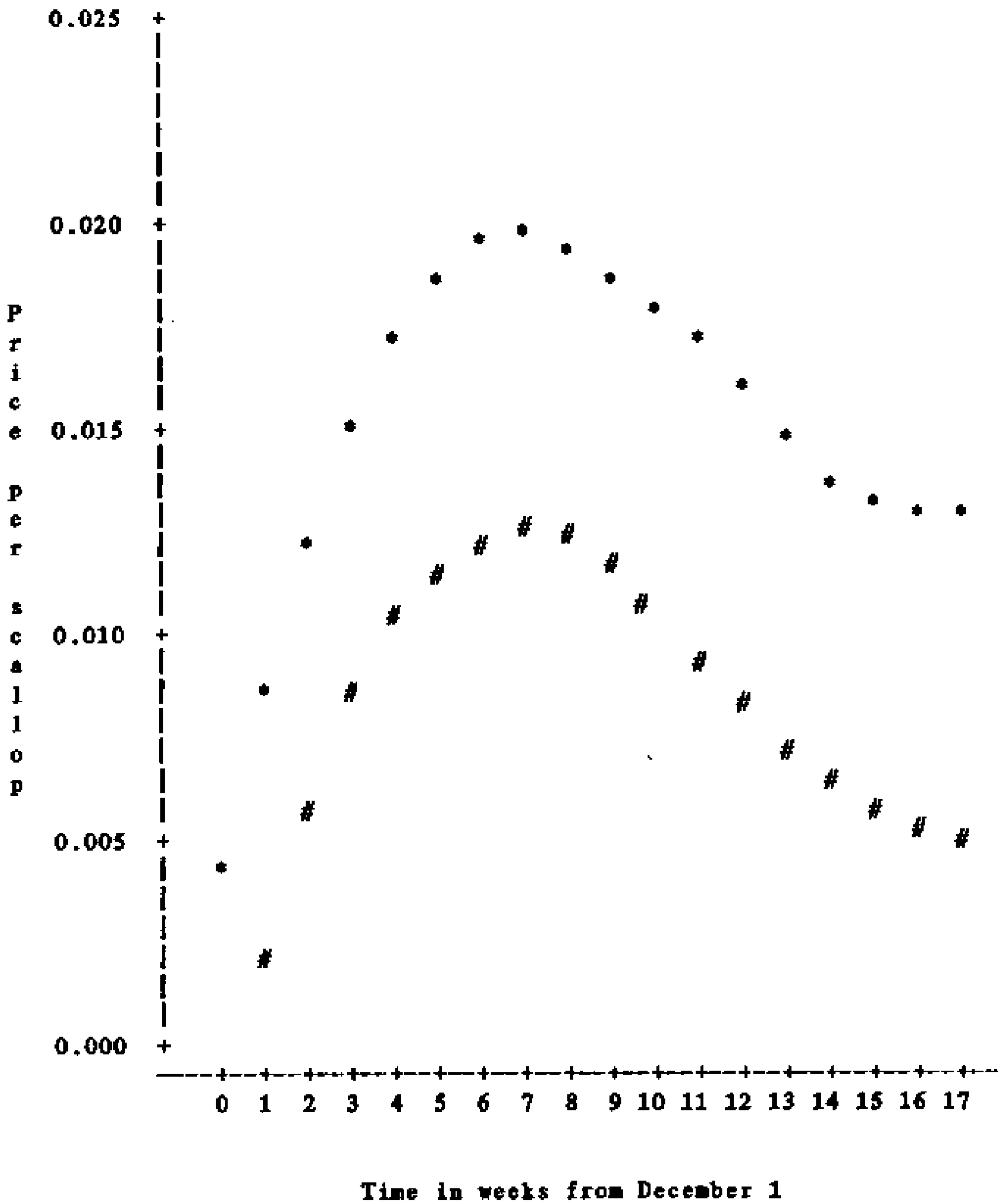


Figure 2. Ex-vessel price per scallop, P(w,t)g(z,t), for North Carolina bay scallops in 1967 dollars. The price equation using 1980-81 values for exogenous variables is indicated by "* * *" and the equation using 1981-82 values is indicated by "# # #".

3.3.3 Fishing Mortality Equation

The catch per unit effort production function is based on the assumption that catch is directly proportional to population size, and that the proportion is constant over time:

$$h(t) = E(t)qx(t).$$

The proportion, $E(t)q$, is called fishing mortality. It is effected by the number of potential scallop fishermen, their harvesting effectiveness, and the limits to effort that are imposed by regulation, such as catch limits and limiting the number of days per week when scalloping is allowed. Fishing mortality is composed of two parts: 1) a standard measure of fishing effort (E), and 2) the catchability coefficient (q). The catchability coefficient is defined as the fraction of a fish stock that is caught by a standard unit of fishing effort (Ricker 1975: p.2). A difficult aspect of any fishery management problem is the definition--and subsequent measurement--of a standard unit of effort. Theoretically, any unit of effort can be used as long as the associated catchability coefficient is known, or can be measured, and as long as all other nominal units of effort in the fishery can be expressed in terms of the standard unit. Almost no information is available for either E or q for this fishery. Consequently, only ad hoc estimates of these variables are possible. Optimal solutions will be calculated for a range of reasonable values for $E(t)q$.

It is desirable to define a standard unit of fishing effort to correspond as closely as possible to the typical, or average, unit of fishing effort that would be observed in the fishery. For this problem, a standard unit of fishing effort is one boat-day, defined to be a 20-foot boat with a maximum holding capacity of 50 bushels pulling 2 drags and fishing for a full day or until capacity is reached. Each standard boat-day is assumed to be manned by the owner and one crew member. This is the most common effort level reported for the fishery (Fricke 1981). A boat capacity limit of 50 bushels is a realistic feature of the bay scallop fishery because of the small size of the boats needed to maneuver in the shallow water environment where bay scallops are found. It will also be assumed that if the boat capacity is reached, fishing will stop for that day. (Under present regulations, returning to the fishing grounds after unloading the catch is illegal because of the daily catch limits.) Individual fishermen may adopt a number of fishing arrangements other than the standard one defined here, but these arrangements would be converted to standard units of fishing effort when applying the model.

Theoretically, the number of fishermen engaged in scallop fishing at any specific moment during the harvest season depends on expected profit (and thus expected catch, price, and fishing costs) and profitability of alternative fisheries or employment opportunites. Consequently, fishing effort <u>should</u> be modelled as an endogenous variable. However, quantitative data on fishing effort are not available for this fishery, precluding this approach. Instead, fishing effort will be taken as a <u>constant</u> throughout the season and will represent an "average" level of fishing effort. Evidence collected by the DMF during enforcement activities indicated that the number of boats observed fishing for scallops tapers off sharply as the season progresses. This is reasonable since profitability depends on the abundance of scallops, which decreases as harvesting proceeds. Since information defining the seasonal availability of fishing effort is not available, an ad hoc estimate of the seasonal average was made.

Now that a standard unit of fishing effort has been defined for the bay scallop fishery, an empirical estimate of it is needed. Fricke (1981) reported that there were approximately 600 scallop fishermen in North Carolina, 75 percent of whom were full-time fishermen (engaged in commercial fisheries all year) and 25 percent of whom were part-time fishermen (someone who had regular employment outside the commercial fishing industry.) This estimate was based on information gathered from key informants in eight communities along the coast where most scallop fishermen reside. Fricke (1981) also reported that a part-time fisherman was about half as active in the fishery as a full-time fisherman. Therefore, the total number of fishermen was adjusted downward to 525, where each is assumed to be operating as a full-time fisherman. Assuming two full-time fishermen per boat, the number of standard units of fishing effort (as defined here) is estimated to be 262. The average number of standard units of fishing effort expected to be active on any given day was assumed to be 180 (69 percent of the maximum level of 262). Assuming a season average of three good fishing days per week (and assuming that the season remains closed on weekends), the weekly effort level was set equal to 540 boat-days (180 x 3) for the entire North Carolina bay scallop fishery. (Note that the use of three fishing days per week here has nothing to do with regulations limiting the number of fishing days per week. It is used simply in recognition that factors such as poor weather will preclude fishing five days per week by all 180 standard units of effort. Note also that the 180 standard units of effort per day will not correspond to empirical counts of fishing boats since the fishing boats will not all be "standard units".)

This ad hoc estimate of fishing effort is generally consistent with the recent historical record of fishing mortality. It is reasonable to expect, however, that the effort level would be higher if the fishery were managed to maximize returns to the harvesting sector. Under optimal management, the returns from scallop fishing may increase and attract a larger number of fishermen. It is thus desirable to calculate the optimal season opening/closing schedule using a larger number of boat-days per week. Optimal opening/closing schedules were determined assuming 750 boat-days per week in addition to solutions assuming 540 boat-days per week.

With effort (E) in units of boat-days, the catchability coefficient (q) is the fraction of the scallop population that is harvested by one boat-day. Since it is defined here to be a constant, it represents an average value over the entire harvest period and over all vessels. In actuality, the catchability coefficient varies from vessel to vessel and even from day to day for the same vessel. For example, as the season progresses scallops are restricted to areas difficult to fish and for which there is a higher q. There is no information available that would identify the value for q. However, possible values can be calculated that are consistent with catch data from previous years and with the ad hoc estimate of the average number of standard units of fishing effort. Using the catch-per-unit-effort production function ($Eq=h/x$), rough estimates of Eq were obtained for the first week in January for eight harvest seasons. (December was not used because of the possibility that quotas had substantially constrained fishing mortality and because the number of fishing days in December varied from year to year.) The average weekly harvest was calculated for January by dividing the January catch by 4.4, the number of weeks in January. The population size for the first week in January was calculated by subtracting the December catch from the population estimate (see Subsection 3.3.5 for methods of estimating total population size). Estimates of Eq were then obtained by dividing the weekly average January catch by the population estimate for January 1. Assuming 180 standard boat-days per day of effort and 2 fishing days per week (recall that regulations have limited the number of allowed fishing days to this number early in the season), an estimate of q for each of the harvest seasons was calculated by dividing the Eq estimate by 360. Resulting estimates of Eq and q are shown below:

| Harvest season | Eq | q |
|---|---|---|
| 1974-75 | 0.088 | 0.00025 |
| 1975-76 | 0.053 | 0.00015 |
| 1976-77 | 0.057 | 0.00016 |
| 1977-78 | 0.108 | 0.00030 |
| 1979-80 | 0.071 | 0.00020 |
| 1980-81 | 0.098 | 0.00027 |
| 1981-82 | 0.102 | 0.00028 |
| 1982-83 | 0.051 | 0.00014 |

On the basis of these calculations, it appears that fishing mortality has ranged from about 5 to 10 percent per week. For the standard unit of effort defined here, this is equivalent to q values ranging from about 0.0001 to 0.0003. Three q values were used in this study to calculate optimal harvesting solutions: 0.0001, 0.0002, and 0.0003. These q values correspond to fishing mortalities ranging from 5 to 16 percent per week for E=540 boat-days per week and 7 to 22 percent per week for E=750. In the absence of more specific information, it is believed that these Eq values bracket expected fishing mortality for this fishery.

Theoretically, the boat capacity (assumed here to be 50 bushels, or 21,750 scallops) could constrain the catch. The harvest model was altered to incorporate this feature by adjusting q when constrained as follows:

$$\text{if } q(t) < \frac{\text{boat capacity}}{\text{population size}}, \text{ then set } q = \frac{\text{boat capacity}}{\text{population size}}.$$

However, for the range of q values and population estimates used in this analysis, the boat capacity was not a constraint. (A catch quota can be incorporated into the model in the same manner by replacing the boat capacity with the catch limit. Quotas were not modelled in this study since they are inherently inconsistent with economic efficiency.)

### 3.3.4 Cost Equation

Fishing costs can be categorized into three groups: 1) fixed costs, such as investment cost of the boat, gear and one-time seasonal maintenance costs, 2) daily fuel costs, and 3) daily opportunity costs of the fisherman. The last two groups represent variable costs, which can be modelled as being proportional to fishing effort. Because fixed costs are constant regardless of the level or timing of fishing effort, they do not affect the optimal timing of the harvest. Consequently, fixed costs will be ignored in this analysis. An estimate of fixed costs was provided by Fricke (1981: p.23): "This is a small boat fishery and the investment of a typical fisherman in boat, gear and operating costs, excluding fuel, is on the order of 500 to 800 dollars per scallop season". Exclusion of these fixed costs will inflate the present value calculation, but the magnitude will be very small relative to the total.

The cost function was therefore modelled as a cost-per-unit-effort function,

$$\text{total cost per week} = cE,$$

where E is the number of boat-days per week and c is a constant cost coefficient. The cost coefficient represents the average variable cost per standard unit of effort, or the average cost per boat day. (Actual costs for an individual fisherman may depart substantially from this average value.)

Whereas the cost coefficient is modelled here as a constant, there is good reason to suspect that both daily fuel costs and opportunity costs of the average fisherman vary over the harvest season. Seasonal unemployment trends (Fricke 1981) suggest that opportunity costs are lowest in January and February when unemployment in the region peaks. In March, alternative fisheries are more available and non-fishing opportunites (such as tourism and construction) increase. Daily fuel costs might also increase as the season progresses. Increases in daily fuel costs would occur as fishermen deplete the resource near their home port and are required to travel farther each week to fish. Also, hours spent towing per day (and thus daily fuel costs) may increase as the resource is depleted and the stock density decreases. This reasoning suggests that daily fuel costs may be a function of stock size rather than effort. However, the relationship between stock density and fuel costs is not known, and so daily fuel costs were modelled on a per-effort basis.

The opportunity cost of scallop fishermen and the daily operating costs were estimated indirectly. Individuals employed in the processing sector were reported to make about 40 dollars per day (assuming eight hours per day) hand-shucking scallops in January, 1982 (<u>News and Observer</u>, Raleigh, N. C., Sunday, January 31, 1982). This wage was taken as an estimate of the opportunity cost of a scallop fisherman. It would be expected that the fisherman would remain in port and shuck scallops if his income from fishing was less than 40 dollars per day. Fricke (1981) cites one frequently mentioned division of income from a day's catch as giving one-third of the gross to the boat to cover operating expenses (including fuel costs) and depreciation, one-third to the owner-captain (operator), and one-third to the crew member. If the opportunity cost of a fisherman is 40 dollars per day, the total minimum daily opportunity cost for the two fishermen would be 80 dollars and daily operating expenses would be 40 dollars using this payment scheme. (Fricke (1981) also reported that daily fuel consumption ranged from 10 to 20 gallons, which is equivalent to about 15 to 30 dollars per day assuming 1.50 dollars per gallon. Thus, the 40 dollar per day operating expense for the boat seems reasonable when other daily non-fuel costs are considered.) Consequently, the total daily cost per standard unit of effort is estimated to be 120 dollars, which is equivalent to 42.55 dollars after conversion to 1967 dollars (determined by dividing the nominal amount by the consumer price index for January, 1981).

As discussed in Chapter 2, opportunity costs of fishermen are difficult to quantify. Depending on relative prices, fishing for oysters or clams might be a better employment alternative than shucking scallops. Alternatively, some fishermen may face the choice of scallop fishing or no employment at all. In this case, their opportunity cost would be much lower than that estimated here. The opportunity costs of scallop fishermen can therefore vary markedly from season to season and from individual to individual. Since this cost estimate affects the optimal season opening/closing schedule, a second (lower) estimate of the cost coefficient was also calculated. Assuming an opportunity cost of 3.50 dollars per hour (rather than the 5.00 dollars per hour used above) and retaining the 40 dollars per day operating cost, an alternative cost per standard unit of effort is 34.04 dollars per day in 1967 dollars. The harvesting problem was solved for both of these cost estimates.

### 3.3.5 Equation of Motion

Because of fortuitous biological characteristics of the North Carolina bay scallop, the change in population number—the equation of motion--can be modelled as equal to the harvest rate, as follows:

$$\dot{x} = - Eqx(t)\,\Phi(t),$$

$$x(0) = x_0.$$

Two features of bay scallop biology that permit this simplification are: 1) there is no recruitment during the potential harvest season and 2) natural mortality is believed to be very low during the potential harvest season, and is assumed to be zero for purposes of this study.

Whereas natural mortality of bay scallops is high during the spring and summer, Division of Marine Fisheries biologists believe that the natural mortality rate is low during the winter months when harvesting occurs. Low natural mortality during this time results because many of the important predators of bay scallops favor warmer temperatures and bay scallops thrive at the cooler winter temperatures. The natural mortality rate is not always near-zero, however. Mass mortalities can occur as a result of extremely cold temperatures and low salinities. But in the absence of estimates of the natural mortality rate, the assumption of zero natural mortality during the potential harvest season is reasonable. (Should subsequent studies reveal significant natural mortality during the harvest season, the problem can be expanded to incorporate natural mortality using an approach similar to that used by Kellogg (1985) for New River shrimp.)

Since there is no recruitment during the harvest season, the recruitment function, F(z,t), collapses to a single initial value for population size, $x_0$. In practice, $x_0$ can be estimated prior to the harvest season by sampling. For the present analysis, five values of $x_0$ that span the range of probable values were selected. The total catch in numbers for nine harvest seasons was approximated by converting monthly catch in pounds to catch in numbers and summing over the monthly values. (See Kellogg (1985) for results.) These season catch totals were then adjusted to probable values for initial population size by dividing the catch total by an estimate of the proportion of the scallop population harvested. This proportion is not known exactly, and probably varies from year to year. However, because of the intensity at which scalloping occurs by some of the local fishermen, it is likely that most of the scallops are harvested each season (Dennis Spitsbergen, Division of Marine Fisheries, personal communication). Therefore, a value of 0.75 was used to calculate population estimates. Resulting estimates ranged from 13 to 33 million scallops (Kellogg 1985). Values of $x_0$ selected for use in the present study were 13, 18, 23, 28 and 33 million scallops.

## 3.4 <u>Calculation of the Optimal Harvesting Period</u>

### 3.4.1 Statement of the Problem

Incorporating the results of Section 3.3 into the harvesting model in Section 3.2, the problem can be restated as follows:

$$\underset{\Phi(t)}{\text{maximize with respect to}} \quad PV = \int_0^T [P(t,w)g(z,t)Eqx(t) - cE]e^{-\delta t}\,\Phi(t)\,dt,$$

$$\text{such that} \quad \dot{x} = -Eqx(t)\,\Phi(t),$$

$$x(0) \text{ given},\ 0 \le t \le T, \text{ and } x(t) \ge 0,$$

where $P(t,w) = a_0 + a_1 INCOME_t + a_3 SEAP_t + a_4 SEAP_{t-1} + a_5 SEAP_{t-2}$

$$+ a_7 CALQ_t + a_8 t + a_9 t^2 + a_{10} t^3,$$

$$g(z,t) = 0.002205[M_{max}(1-e^{-B(C,t)}) + M_0 e^{-B(C,t)}],$$

$$B(C,t) = b_1(t+4.3) + b_2 C + b_3 C^2/(t+4.3)$$

$$M_{max} = m_1 S_t^3,$$

$$S_t = S_{max}(1-e^{-(c_1(t+4.3)+c_2C)}) + S_0 e^{-(c_1(t+4.3)+c_2C)}$$

$$C = 20.203(t+4.3) - 1.012(t+4.3)^2 + 0.027(t+4.3)^3,$$

t = time in weeks starting from December 1, and

$\Phi(t)$ = the decision variable ( $\Phi(t)=0$ implies a closed season and $\Phi(t)=1$ implies an open season).

Coefficients were estimated in Section 3.3 as follows:

| | | | |
|---|---|---|---|
| $a_0$ = | -4.24904127 | $M_0$ = | 2.522 |
| $a_1$ = | 0.00473008 | $b_1$ = | -0.4415 |
| $a_3$ = | -1.85448147 | $b_2$ = | 0.0969 |
| $a_4$ = | 0.56224238 | $b_3$ = | -0.0034 |
| $a_5$ = | 1.69072116 | $m_1$ = | 0.0270 |
| $a_7$ = | -0.0000005476 | $S_{max}$ = | 6.378 |
| $a_8$ = | 0.38661194 | $c_1$ = | -0.0298 |
| $a_9$ = | -0.04133764 | $c_2$ = | 0.0065 |
| $a_{10}$ = | 0.00119521 | | |

Exogenous variables were assigned the following values:

E = 540 or 750 standard boat-days per week,
q = .0001, .0002 or .0003,
c = 42.55 or 34.04 (1967 dollars),
$\delta$ = 0.001827,
$S_0$ = 5.9 centimeters,
$x_0$ = 13, 18, 23, 28, or 33 million scallops,

and the two sets of values for the three exogenous demand variables are shown below.

| Variable | High price (1980-81) | Low price (1981-82) |
|---|---|---|
| $INCOME_t$ | 882 | 887 |
| $SEAP_t=SEAP_{t-1}=SEAP_{t-2}$ | 2.00 | 1.31 |
| $CALQ_t$ | 531,369 | 1,084,457 |

In summary, there are two price estimates, two cost estimates, five population size estimates, three q estimates and two effort levels. Effort is held constant throughout the season, the scallop growth rate assumes a "normal" temperature regime and assumes growth is the same for all areas. No quotas are imposed, and fishing is allowed Monday through Friday. Solving the harvesting problem for each of the possible combinations results in 120 separate solutions. The range of values for each variable was selected with the purpose of bracketing values most likely to occur. Consequently, the 120 optimal solutions provide general guidelines for when to open the scallop season when no prior information on any of the exogenous variables is available.

3.4.2 Solution Procedure

As discussed in Chapter 2, the maximum principle is used to solve for the optimal opening/closing schedule, $\Phi(t)$. The Hamiltonian for this problem is

$$H(t) = \{[P(t,w)g(z,t)Eqx(t)-cE]e^{-\delta t} - \lambda(t)Eqx(t)\}\ \Phi(t),$$

which leads to the following switching function:

$$\Phi(t) = \begin{cases} 1 & \text{if} \quad [P(t,w)g(z,t)Eqx(t)-cE]e^{-\delta t} - \lambda(t)Eqx(t) \ > 0 \\ 0 & \text{if} \quad [P(t,w)g(z,t)Eqx(t)-cE]e^{-\delta t} - \lambda(t)Eqx(t) \ \leq 0. \end{cases}$$

The system of differential equations is as follows:

$$\Phi=0 \implies \dot{x}=0 \text{ and } \dot{\lambda}=0,$$

$$\Phi=1 \implies \dot{x} = -Eqx(t), \quad x_o \text{ given},$$

$$\dot{\lambda} = \lambda(t)Eq - P(t,w)g(z,t)Eqe^{-\delta t}.$$

Sufficient conditions for a solution can not be derived because boundary conditions for the adjoint equation are not specified. (That is, only the general solution of the adjoint equation can be obtained; the particular solution requires that $\lambda$ be known at some point in time.) The optimal solution is obtained by varying $\lambda(0)$ (designated as $\lambda_o$) until the $\Phi(t)$ corresponding to the maximum net present value of the season harvest is identified.

The optimal opening/closing schedule was determined to the nearest week. Further precision is probably not warranted in view of the many assumptions and approximations that were made in specifying the problem. The algorithm used to solve for the optimal $\Phi(t)$ is presented in Appendix A. The program steps through the potential harvest season week by week. The switching function is solved at the beginning of each week to see if the season should open or not. If the switching function is negative, the program skips to the beginning of the next week and repeats the check. If it is positive, the two differential equations are solved using a fourth-order Runge-Kutta numerical procedure (Wolfe and Koelling 1983). The harvest and net present value of the harvest for the week is also calculated within the Runge-Kutta algorithm. After determining the new x and $\lambda$, the program advances to the beginning of the next week and checks to see if the season should remain open.

To demonstrate the switching point with respect to $\lambda$, it is necessary to rearrange algebraically the switching function as follows:

$$\phi = \begin{cases} 1 & \text{if} \quad \lambda(t) < [P(t,w)g(z,t) - c/qz(t)]e^{-\delta t} \\ 0 & \text{if} \quad \lambda(t) \geq [P(t,w)g(z,t) - c/qz(t)]e^{-\delta t} \end{cases}$$

The term on the right-hand side of the inequality sign is the discounted net revenue per scallop harvested. The switching function in this form indicates that the season should remain closed as long as the user cost per scallop, $\lambda$, is greater than the discounted net revenue per scallop harvested. The season should open at the point where $\lambda$ equals the potential discounted net revenue per scallop and remain open as long as the marginal discounted net revenue is greater than the marginal user cost. (This is nothing more than the familiar profit maximization rule of MR=MC.)

An example of the procedure used to obtain the optimal solution is illustrated graphically in Figures 3 and 4. This example was based on the solution to one of the 120 combinations indicated above. In this problem, $\lambda(t)$ is a monotonically decreasing function of time as long as $\lambda(0) < P(t,w)g(z,t)e^{-\delta t}$. There is no change in $\lambda$ until the season opens, after which $\lambda$ decreases until it gets to zero or until the season closes again (Figure 3). The marginal discounted net revenue curve increases to a peak between the seventh and eighth weeks and then decreases again as the price per scallop decreases later in the season. A $\lambda_o$ equal to 0.011 is so high that it does not intersect the marginal discounted potential net revenue curve and the season never opens. Choosing a smaller $\lambda_o$, $\lambda_o$=0.010, results in a season opening in the seventh week (t=6). However, the season closes again after the ninth week with $\lambda$ still greater than zero. From the necessary condition that $\lambda(T)=0$ we know that $\lambda_o$=0.010 cannot be optimal. $\lambda_o$=0.007 is tried next. This choice results in a season opening in the fifth week (t=4), and $\lambda(T)=0$ as required.

At this point $\lambda_o$=0.007 is a contender for the optimal $\lambda_o$. It meets the necessary conditions. However, several other values for $\lambda_o$ also meet these necessary conditions. The optimal solution is found by methodically searching for the $\lambda_o$ that corresponds to the maximum net present value of the season's harvest. This is illustrated in Figure 4 for the example at hand. As $\lambda_o$ is increased, the cumulative net present value of the harvest increases to a maximum when $\lambda_o$ is between 0.008 and 0.009. This optimum corresponds to a season opening at the beginning of the sixth week. Since the solution is obtained only to the nearest week, there is a range of $\lambda_o$s that are optimal.

The lowest marginal discounted net revenue curve shown in Figure 3 is for $\lambda(t)=0$. This represents the present situation in the fishery where the marginal user cost is disregarded. In this example, the season would open (that is, the fishery would become profitable) at the beginning of the third week and would become unprofitable by the end of the ninth week (a seven-week interval). The cumulative net present value for this unregulated case is 45,999 (1967 dollars). The <u>optimal</u> season (regulated case) starts at the beginning of the sixth week and becomes unprofitable after the eleventh week

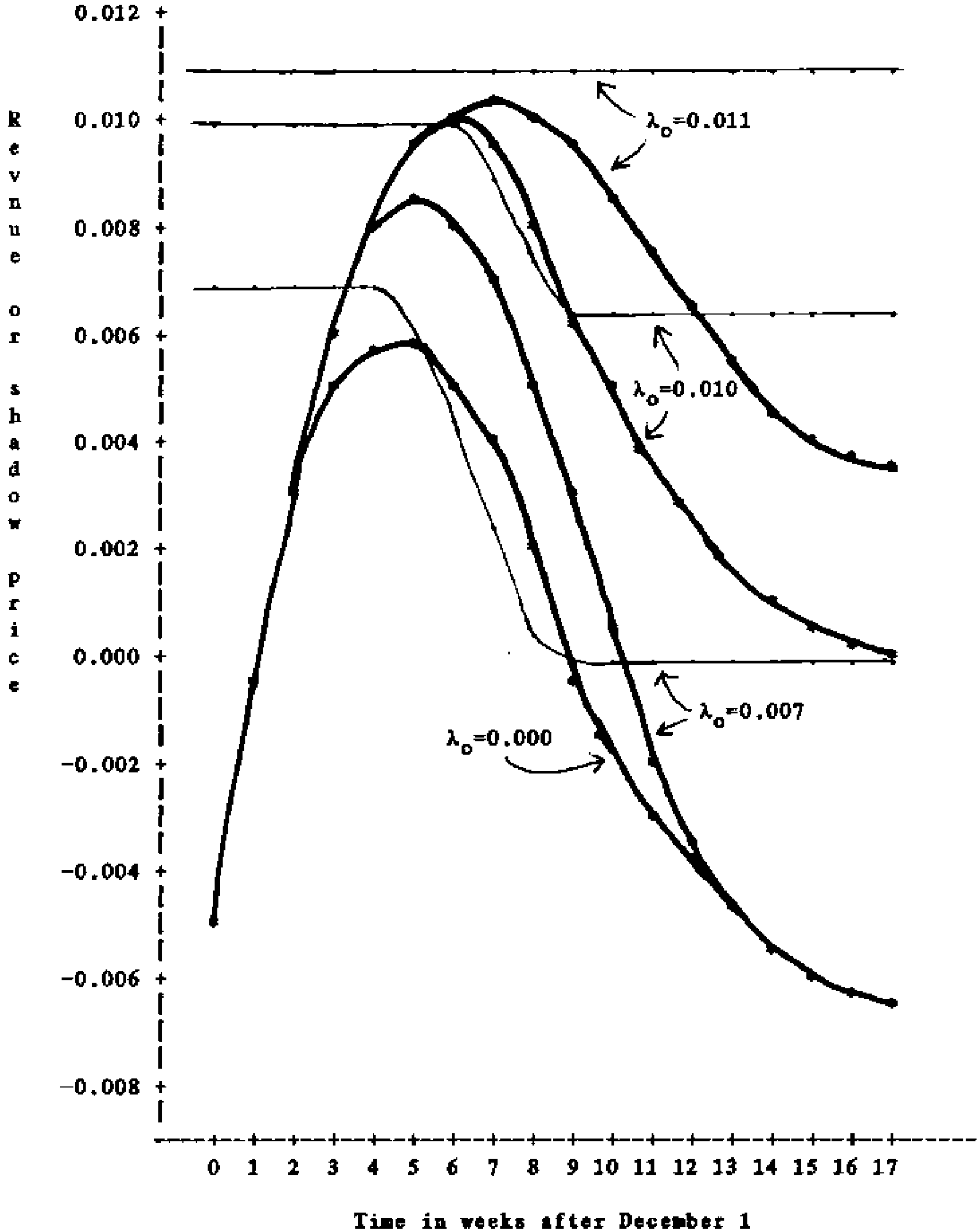


Figure 3. A graphical illustration of the procedure for solving for the optimal harvest period (see text). The marginal discounted potential net revenue per week is indicated by "——" and λ is indicated by "——". Revenue and shadow price are in 1967 dollars.

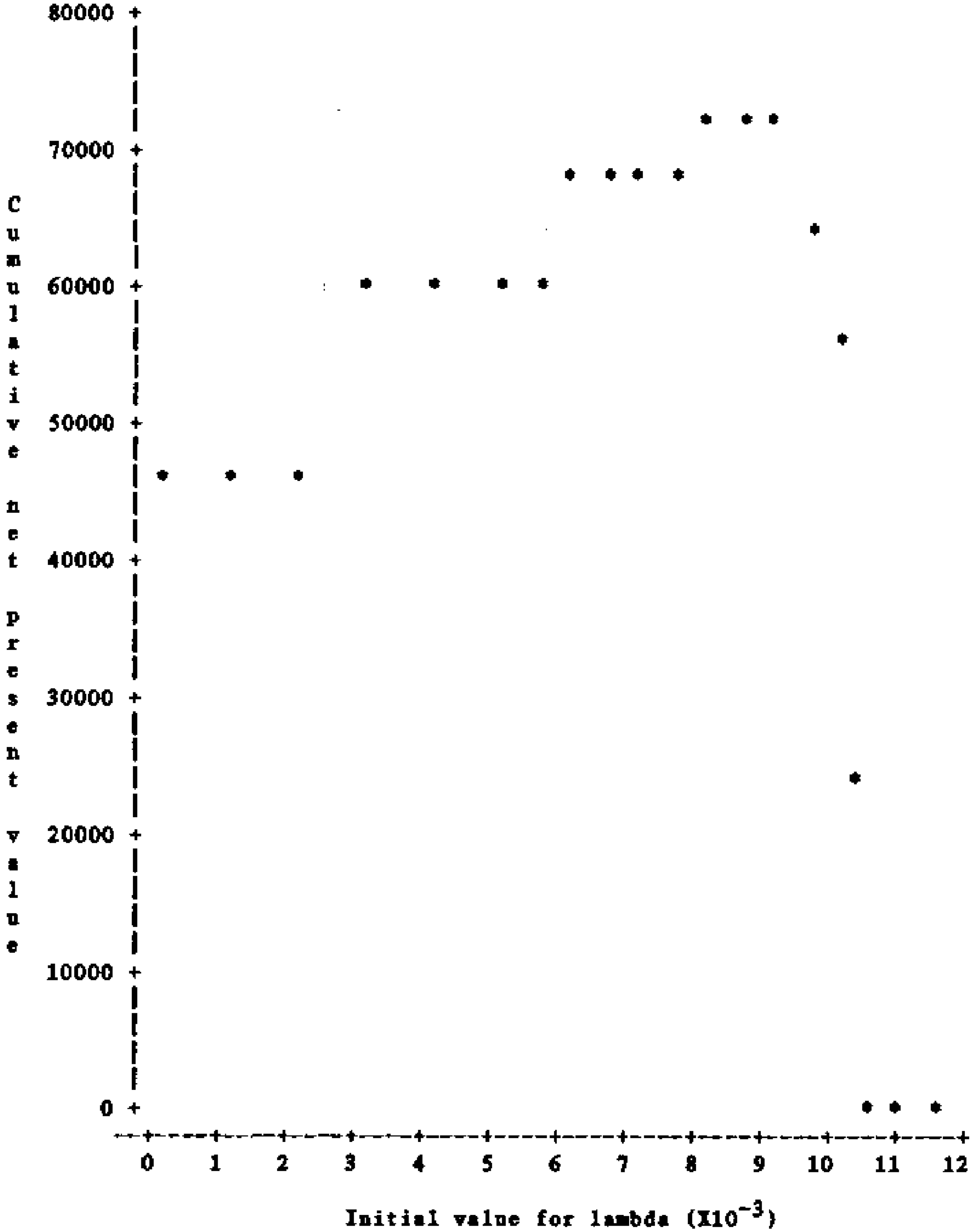


Figure 4. The value of the objective function—the cumulative net present value of the harvest (in 1967 dollars)—plotted against values for $\lambda_o$. In this example, the objective function is maximized when $\lambda_o$ is between 0.008 and 0.009.

(a six-week interval), resulting in a cumulative net present value of 71,919 (1967 dollars). The conclusion from this example is that delaying the opening of the season increased the commercial value of the resource, and suggests that the potential gains from bioeconomic management are substantial.

Obtaining the optimal $\lambda_0$ also results in an optimal season closing time. This is important in establishing the optimal present value of the harvest. However, it would not actually be regulated by the regulatory agency. The optimal season closing time represents the time when it is no longer profitable to harvest scallops under the assumptions of the model. In practice, the fishermen will determine when to stop fishing. The focus here is on opening the season in such a manner as to be consistent with profit maximization and economic efficiency.

The same reasoning applies to the unregulated case (where $\lambda(t)=0$). The season determined for the unregulated case represents the time when it is profitable to harvest scallops under the assumptions of the model. In the above example, the unregulated fishery did not operate until the third week in December, even though fishing during the first two weeks was possible. In the actual fishery, fishermen are observed harvesting scallops whenever the season is open. This discrepancy between the model and "reality" occurs because of simplifying assumptions used to develop the model. For example, the model assumes that all fishermen are identical and have the same opportunity costs. Some fishermen would be fishing when the returns were below the opportunity costs assumed in the model. Consequently, any comparison between the optimal solution (regulated case) and the unregulated case must be made using the same set of assumptions. This requirement is met by contrasting the optimal solution to the unregulated solution obtained from the model with $\lambda(t)=0$. (The distinction between the model and what may be observed in an actual fishery is important for understanding how to interpret the results of the model, but does not diminish their applicability.)

Only a single season opening will result for the scallop harvesting problem under the assumptions of the model. This is obvious from Figure 3. Even without harvesting, the marginal discounted net revenue curve decreases after the seventh week. Growth in the value of the stock after this time is negative, indicating that delaying the season opening beyond the eighth week would never be optimal. If harvesting could be done in a single week, it would take place during the seventh or eighth week. Since there are constraints on the rate at which harvesting can take place (limited here by Eq), the optimal solution is a blocked interval balanced roughly about the seventh week. (See Clark (1976, p. 56) for a discussion of blocked intervals in conjunction with the fisheries optimal control model.)

### 3.4.3 Results

The results of the 120 solutions are summarized in Appendix B, Table B1. Optimal season openings ranged from the fifth week ($t=4$) to the eighth week ($t=7$). The most important determinant of the season opening was population size. At low Eq levels with all factors except population size constant, solutions ranged from opening at the fifth week (high initial population size) to not opening at all (low initial population size). The effects of $x_0$ on the season opening were less pronounced at the higher Eq values.

Price and cost also had an effect on the season opening. For a given population size and fishing mortality, the season opening was generally one week earlier at the high price level than at the low price level. The two cost levels had a similar effect (the lower the cost, the earlier the season opening).

The predominant effect of fishing mortality (Eq) on the season opening was in determining whether it was profitable to fish or not. At low Eq values (less than 0.08), it was generally profitable to fish only at the higher population levels. Over the range of Eq values from 0.118 (q=0.0002 and E=540) to 0.225 (q=0.0003 and E=750), the optimal season opening varied by a maximum of one week (all other inputs constant) for about one-half of the input combinations and did not change for the remaining input combinations.

The corresponding season for the unregulated case ($\lambda(t)=0$) was also determined for each of the 120 input combinations. Results are presented in Appendix B, Table B2. Start of fishing ranged from the first week (t=0) to the seventh week (t=6). The unregulated case is contrasted with the optimal solutions for E=540 in Table 4. Typically, the optimal solution was to delay opening the season two to three weeks past the start of fishing in the unregulated case. Delaying the season opening substantially increased the present value of the harvest for all comparisons. (It is important to remember that the "unregulated case" determined here isn't completely unregulated. The model still assumes that fishing is not permitted on weekends or at night, and gear restrictions on the design and weight of the drag remain in force.)

### 3.5 Useful Future Research

From the many ad hoc estimates and ranges of values used in the bay scallop harvesting problem, it is obvious that more research is needed before the power of this model can be used to its fullest as an aid to the promulgation of optimal regulation. Foremost on the "need list" is a catch-effort dataset. Complete weekly catch statistics including 1) the number of hours fished per boat, 2) characteristics of the fishing effort such as boat size and crew size, and 3) size and value of the catch can be used to estimate the original population size and the catchability coefficient. It can also be used to develop a relationship between profitability and the supply of fishing effort. Development of a supply equation for fishing effort is particularly useful in evaluating the impact of management practices that differ from current practices. This information would need to be collected only until reasonable q estimates have been determined and a supply equation for effort has been developed.

The price equation will need to be continually updated. The main objective of the price equation is to forecast. Thus it should perform best when it is fitted with the most recent data available. It would be desirable to update the equation before each season. In addition, a price prediction equation that was based on weekly prices would perform much better in the model than the present equation, which was based on monthly data. Weekly price data can be obtained in conjunction with the catch-effort study described above.

Another area for more study is the estimation of costs, particularly the opportunity cost for the "average" scallop fisherman. As seen in the last section, costs play an important role in determining the optimal season. Fishermen with very low opportunity costs would prefer to open the season slightly earlier than those with higher opportunity costs. They would also fish longer in the latter part of the season. Thus, there is no season opening that is optimal for all individuals. Additionally, there is probably a seasonal component to fishing costs that is not included in this analysis that may affect the optimal solution. More information on opportunity costs of scallop fishermen would permit a more refined analysis of the harvesting problem.

The final area for additional research is the quantification of natural mortality during the harvest season. The solutions presented here are based on the assumption that there is no natural mortality during the harvest season. If there are significant sources of natural mortality competing with the fishermen for the stock, then the optimal season opening would be earlier than presented here.

Table 4. Summary of harvesting solutions for the North Carolina scallop fishery—both regulated and unregulated--for 60 combinations of exogenous variables. Present value is in 1967 dollars. Only results for an effort level of 540 boat-days per week are presented. (See Appendix B for a full presentation of results.)

| | q=0.0001 | | | | q=0.0002 | | | | q=0.0003 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | unregulated[a] | | regulated | | unregulated[a] | | regulated | | unregulated[a] | | regulated | |
| $x_e$[b] | fishing period | present value | optimal season | present value | fishing period | present value | optimal season | present value | fishing period | present value | optimal season | present value |
| | | | | | Price=low[c], Cost=42.55 | | | | | | | |
| 13 | none | --- | none | --- | none | --- | none | --- | 5 | -68 | 7 | 1,573 |
| 18 | none | --- | none | --- | 6 | -38[d] | none | --- | 3-5 | 746 | 6-8 | 17,418 |
| 23 | none | --- | none | --- | 4-6 | 4,052 | 6-8 | 10,239 | 3-7 | 23,122 | 6-9 | 42,861 |
| 28 | none | --- | none | --- | 3-7 | 12,453 | 5-8 | 28,110 | 2-7 | 29,195 | 5-9 | 73,701 |
| 33 | none | --- | none | --- | 3-8 | 36,233 | 5-9 | 51,870 | 2-8 | 58,883 | 5-10 | 107,737 |
| | | | | | Price=low, Cost=34.04 | | | | | | | |
| 13 | none | --- | none | --- | none | --- | none | --- | 4-6 | 2,214 | 6-7 | 8,304 |
| 18 | none | --- | none | --- | 4-6 | 1,983 | 6-8 | 6,829 | 3-7 | 16,115 | 6-9 | 31,967 |
| 23 | none | --- | none | --- | 3-7 | 12,669 | 6-9 | 25,276 | 2-7 | 26,911 | 5-9 | 62,970 |
| 28 | 6 | -107 | 7 | 118 | 3-8 | 37,361 | 5-9 | 49,510 | 2-8 | 57,689 | 5-10 | 98,006 |
| 33 | 4-7 | 1,643 | 6-8 | 6,084 | 2-9 | 47,036 | 5-10 | 77,237 | 2-9 | 90,917 | 5-10 | 134,934 |
| | | | | | Price=high, Cost=42.55 | | | | | | | |
| 13 | none | --- | none | --- | 4-5 | -403 | 7-8 | 3,818 | 2-5 | 4,144 | 6-8 | 29,457 |
| 18 | none | --- | none | --- | 2-6 | 7,025 | 6-9 | 31,065 | 1-6 | 21,990 | 5-9 | 78,080 |
| 23 | 5,7[e] | -614 | 7 | 932 | 2-8 | 45,999 | 5-10 | 71,919 | 1-8 | 67,819 | 5-10 | 136,033 |
| 28 | 4-8 | 10,408 | 6-9 | 13,838 | 1-9 | 66,814 | 5-11 | 119,718 | 1-9 | 121,070 | 5-11 | 199,263 |
| 33 | 3-9 | 28,925 | 5-10 | 36,439 | 1-10 | 115,532 | 5-12 | 171,734 | 0-9 | 120,886 | 5-12 | 265,578 |

Table 4. (continued)

| | q=0.0001 | | | | q=0.0002 | | | | q=0.0003 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | unregulated[a] | | regulated | | unregulated[a] | | regulated | | unregulated[a] | | regulated | |
| $x_0$[b] | fishing period | present value | optimal season | present value | fishing period | present value | optimal season | present value | fishing period | present value | optimal season | present value |
| | | | | | Price=high, Cost=34.04 | | | | | | | |
| 13 | none | --- | none | --- | 3-6 | 6,376 | 6-8 | 15,474 | 2-7 | 22,837 | 5-9 | 47,569 |
| 18 | 6 | 115 | 7 | 335 | 2-8 | 33,227 | 5-10 | 53,920 | 1-7 | 51,240 | 5-10 | 104,096 |
| 23 | 3-8 | 5,549 | 6-9 | 13,309 | 1-9 | 59,274 | 5-11 | 101,736 | 1-9 | 103,842 | 5-11 | 167,077 |
| 28 | 2-9 | 23,489 | 5-10 | 37,511 | 1-10 | 109,056 | 4-12 | 154,969 | 0-9 | 113,619 | 5-12 | 234,114 |
| 33 | 2-11 | 55,442 | 4-11 | 67,695 | 1-11 | 162,232 | 4-13 | 212,422 | 0-10 | 165,852 | 5-13 | 303,550 |

[a]The unregulated solution was determined by setting λ equal to zero, which is equivalent to setting the user cost equal to zero, as occurs in the unregulated open access fishery.

[b]Millions of scallops.

[c]The "high" price was produced by solving the price equation using the 1980–1981 average of the exogenous variables (sea scallop price, calico scallop landings, and income). The "low" price was produced using the 1981–1982 average of these variables.

[d]Negative values resulted because there was a positive net return at the beginning of the week, which was offset by losses in the latter part of the week. Recall that the decision to harvest was made on a weekly basis.

[e]The fishery was not profitable during the second harvest week, but returned to being profitable in the third week owing to growth in value.

Note: The season is in weeks where the first week is the first seven days in December. Numbering begins with zero. For example, an optimal season of "5 to 12" denotes that the season opens at the <u>beginning</u> of the sixth week (delaying the opening five weeks past December 1) and remains open <u>through</u> the thirteenth week.

CHAPTER 4. INCORPORATING UNCERTAINTY INTO THE MANAGEMENT DECISION

## 4.1 Introduction

Application of optimal control models to fisheries management can greatly enhance the regulator's ability to promulgate regulations that are consistent with maximization of the social value of the fishery. However, optimal control theory—like all mathematical optimization techniques—has two difficult prerequisites:

1) a model that captures the essential biological and economic elements of the fishery in question, and

2) perfect knowledge of the future values of exogenous variables (such as water temperature, prices of related goods, opportunity costs of fishermen and gear).

Models can be improved and new models developed as feedback from the use of the models motivates additional research and data collection. But future values of exogenous variables will never be known with certainty.

The problem that arises from uncertainty is apparent in the bay scallop harvesting problem. Five variables were assigned more than one possible value, resulting in 120 separate solutions. Four possibilities for the optimal time to open the season resulted. Which one should the regulator choose? Some variables—such as initial population size—might be estimated more closely by collecting additional data before making the management decision, but the problem of uncertainty remains.

Another point of difficulty associated with uncertainty is risk aversion. If future values were known, the optimal solution would be preferred by all members of society, assuming they could agree on the objective function and opportunity costs. But with uncertainty comes a choice of two or more management strategies, and with that comes the risk of being wrong. Suppose a regulator chose only one set of exogenous variables, solved the optimum control model and promulgated management regulations. Some fishermen might prefer to use a smaller population size in the model, for example, since there would be a lower probability that the actual population would fall below it. In doing so, they would be expressing a preference for management strategies corresponding to a lower but more certain income over those corresponding to a higher but more uncertain income. In this case, the fishermen are being risk-averse. Most individuals are risk averse when faced with uncertainty, but to varying degrees. Consequently, it is not possible to obtain a single solution that pleases everyone in an atmosphere of uncertainty.

Random processes also affect decision-making. For example, unusually favorable conditions will cause individual scallops to grow more rapidly. Unusually unfavorable conditions will cause less rapid growth and may cause mortality. To include these effects in the model, a stochastic term could be added to the differential equation, as follows:

$$\dot{x} = F(x,t,z) - M(x,t,z) - Q(x,t,y)\,\phi(t) + \sigma(x)dv$$

where v(t) is a Weiner process (Malliaris and Brock 1981). A Weiner process is a Brownian motion process that over any finite interval has a Normal, zero mean, unit variance distribution, independent of the distribution over any non-overlapping interval.

Pindyck (1984) has investigated the effects of this type of randomness in markets for renewable resources. He concludes that in general, given a particular stock level, the net effect of uncertainty on the optimal rate of harvest is indeterminate. There are effects that tend to increase the optimal harvest rate and an effect that tends to reduce it. Even if all functions (such as F, M, and Q) were known precisely, problems of uncertainty might arise due to this random component.

Economic decision theory can be used to partially alleviate these problems of uncertainty in making management decisions (Winkler 1972). It requires a complete set of alternative actions, an estimate of the benefits that would result for each set of exogenous variables, and probabilities for each set of exogenous variables. The selection of these probabilities arises from the decision maker's preconception of the likelihood of each outcome, and thus incorporates the judgment of the manager into the decision making process.

The purpose of this chapter is to illustrate the use of stochastic dominance--a decision theory technique for making decisions under uncertainty. Stochastic dominance rules delineate a set of actions (such as alternative season openings) that would be preferred by <u>all</u> risk-averse individuals. Actions not meeting this criteria can be safely discarded by the fishery manager. The technique is applied to the results of the bay scallop harvesting problem. A payoff matrix with a hypothetical set of probabilities is developed and presented in Subsection 4.2, and stochastic dominance is applied to the problem in Subsection 4.3.

## 4.2 <u>Payoff Matrix</u>

A payoff matrix is a table showing the benefits for each action and each "state of the world". The payoff matrix for the bay scallop harvesting problem with q=0.0002 and E=540 is presented in Table 5. In this example, the states of the world are represented by combinations of three exogenous variables--price level, cost level and population size. The "actions" being considered by the decision maker are the four alternative season openings (t=4, 5, 6 or 7).

Benefits were measured as the cumulative net present value of the total harvest. These were determined by finding the optimum λ(0) <u>after</u> fixing the opening date to one of the four alternatives. The cumulative net present value associated with this $\lambda(0)$ is the maximum payoff for a given opening date and state of the world (that is, a constrained solution). Use of these values in the payoff matrix implicitly assumes that fishermen will optimize their fishing effort subsequent to the season opening, thus stopping at exactly the optimal time. It is probably not possible for the harvesting sector to respond in this way, but the assumption is necessary to provide a common basis for calculating payoffs. Payoffs associated with the unconstrained optimal solutions are indicated by an asterisk in Table 5.

By construction, none of the four actions dominates the others. That is, each action is optimal for at least one state of the world. This occurs because each alternative was obtained as a solution to the optimal control model. Examination of the payoff matrix indicates, however, that most of the optimal solutions are associated with t=5 or t=6.

In addition to calculating benefits for each outcome, probabilities must be assigned to each value of the exogenous variables. The selection of these probabilities is important, as the choice may change if the probabilities change. For variables controlled largely by physical factors—such as water temperature--probabilities can be assigned on the basis of distributions of past events. For other variables, probabilities must be assigned subjectively, reflecting the decision maker's best judgment. For illustration purposes, probabilities were arbitrarily assigned to the two price levels, two cost levels and five population sizes in the bay scallop problem as follows:

| | |
|---|---|
| $Prob(x_0=13{,}000{,}000) = 1/9$ | Prob(high price level) = 2/3 |
| $Prob(x_0=18{,}000{,}000) = 2/9$ | Prob(low price level) = 1/3 |
| $Prob(x_0=23{,}000{,}000) = 3/9$ | |
| $Prob(x_0=28{,}000{,}000) = 2/9$ | Prob(high cost level) = 1/3 |
| $Prob(x_0=33{,}000{,}000) = 1/9$ | Prob(low cost level) = 2/3 |

The joint probability for each of the 20 outcomes was calculated as the product of the three probabilities associated with each set of exogenous variables. This assumes the variables are independent, which is a reasonably safe assumption here. If independence cannot be assumed, however, conditional probabilities should be used.

Using these probabilities, the expected value for each of the four alternative actions was calculated (Table 5). Opening the season in the sixth week (t=5) has the highest expected value (71,135), followed closely by t=4 (69,871) and t=6 (59,226). Opening the season in the eighth week (t=7) results in a much lower expected value (20,947). A risk-neutral individual would select t=5 as the best season opening, since it has the highest expected payoff (given the selected probabilities). A risk-averse individual, however, is more interested in the probabilities associated with the lower payoffs.

Table 5. Payoff matrix of cumulative net present value (1967 dollars) for the bay scallop harvesting problem (q=0.0002, E=540 boat-days). Asterisks indicate maximum value for each state of the world.

| State of the world | Week of Season Opening | | | | Joint probability |
|---|---|---|---|---|---|
| | t=4 | t=5 | t=6 | t=7 | |
| Price=low, Cost=high[a] | | | | | |
| $x_0$=13[b] | 0 | 0 | 0 | 0 | 0.012 |
| $x_0$=18 | 0 | 0 | 0 | 0 | 0.025 |
| $x_0$=23 | 4052 | 8866 | 10239* | 6613 | 0.037 |
| $x_0$=28 | 22893 | 28110* | 28406 | 12982 | 0.025 |
| $x_0$=33 | 47180 | 51870* | 44280 | 19351 | 0.012 |
| Price=low, Cost=low | | | | | |
| $x_0$=13 | 0 | 0 | 0 | 0 | 0.025 |
| $x_0$=18 | 1983 | 5753 | 6829* | 4781 | 0.049 |
| $x_0$=23 | 21175 | 25036 | 25276* | 11150 | 0.074 |
| $x_0$=28 | 46594 | 49510* | 46537 | 17519 | 0.049 |
| $x_0$=33 | 74936 | 77237* | 67799 | 23888 | 0.025 |
| Price=high, Cost=high | | | | | |
| $x_0$=13 | -403 | 2460 | 3789 | 3818* | 0.025 |
| $x_0$=18 | 26919 | 30165 | 31065* | 13406 | 0.049 |
| $x_0$=23 | 68376 | 71919* | 64877 | 23432 | 0.074 |
| $x_0$=28 | 117791 | 119718* | 98689 | 33457 | 0.049 |
| $x_0$=33 | 170996 | 171734* | 132500 | 43483 | 0.025 |
| Price=high, Cost=low | | | | | |
| $x_0$=13 | 12025 | 14895 | 15474* | 7918 | 0.049 |
| $x_0$=18 | 51637 | 53920* | 49197 | 17943 | 0.099 |
| $x_0$=23 | 100642 | 101736* | 83008 | 27969 | 0.148 |
| $x_0$=28 | 154969* | 151419 | 116820 | 37994 | 0.099 |
| $x_0$=33 | 212422* | 201102 | 150632 | 48020 | 0.049 |
| Expected value[c] | 69871 | 71135 | 59226 | 20947 | |
| Lowest payoff | -403 | 0 | 0 | 0 | |
| Next-to-lowest payoff | 0 | 2460 | 3789 | 3818 | |

[a] low cost = 34.04, high cost = 42.55 dollars per boat-day.
[b] Millions of scallops

[c] Expected value = $\sum_j P_j X_j$,

where $P_j$ is the probability of the jth state of the world and $X_j$ is the payoff for the jth state of the world.

### 4.3 Application of Stochastic Dominance

Stochastic dominance rules were derived to choose between two actions (such as alternative season openings) by comparing the payoff probability distributions. As indicated above, a risk-neutral decision maker needs only an expected value to make a decision. But a risk-averse decision maker needs to know what the tradeoffs are for the entire range of possibilities. Consider, for example, the choice between opening the bay scallop season at t=5 versus t=7. The probability distributions for these two actions are contrasted in Figure 5. Examination of Figure 5 indicates that most of the distribution for t=7 is to the left of the distribution for t=5, indicating that it is associated with lower payoffs in general. (The expected value for opening the season at t=5 is over three times that for t=7.)

Stochastic dominance rules provide criteria that would be acceptable to all risk-averse decision makers for selecting one distribution over another. When one distribution can be shown to be preferred, it is said to "dominate" the other distribution. The dominated distribution--and it's corresponding action--can then be eliminated from the list of alternatives. A good discussion of stochastic dominance, including mathematical proofs and examples, can be found in Anderson (1974). Only material essential for understanding and applying the procedure is repeated here.

There are two categories of stochastic dominance that are used in this paper:

1) first degree stochastic dominance (FSD), which applies to all individuals, including those who are risk-loving and risk-neutral, and

2) second degree stochastic dominance (SSD), which applies only to risk-averse decision makers.

Additional degrees of stochastic dominance can be generated (see Anderson (1974)), but they are applicable to smaller sets of decision makers.

The rules of stochastic dominance come from the following two theorems (Anderson 1974):

Theorem 1: The probability distribution for action A dominates the probability distribution for action B by FSD if and only if the cumulative probability distribution for action A is less than or equal to the cumulative probability distribution for action B at all payoffs, with strict inequality for at least one payoff.

Theorem 2: The probability distribution for action A dominates the probability distribution for action B by SSD if and only if the cumulative area under the cumulative probability distribution curve for action A is less than or equal to that for action B at all payoffs, with strict inequality for at least one payoff.

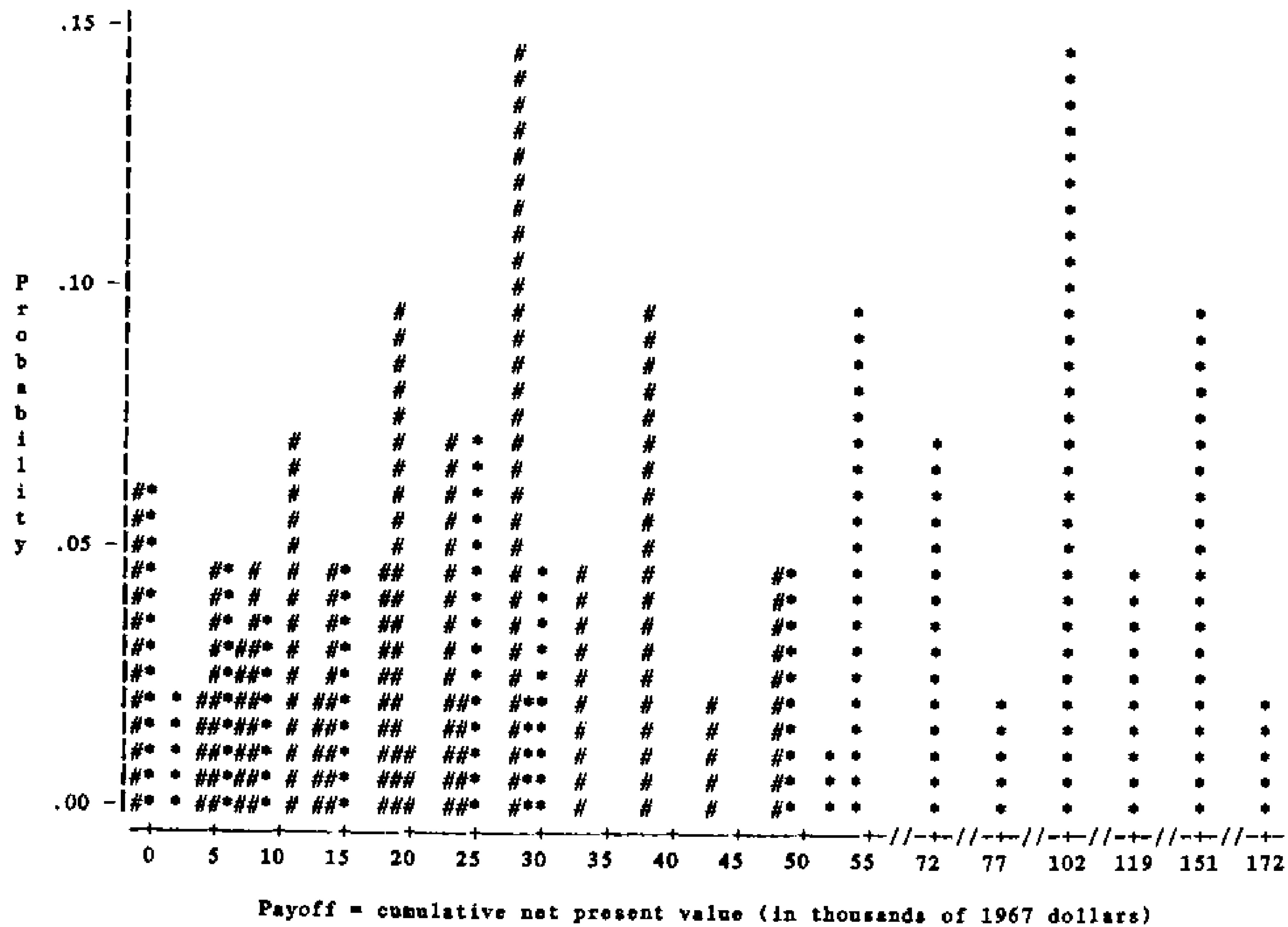


Figure 5. Comparison of the payoff distribution functions for two season opening alternatives: ''******'' represents season opening at t=5 and ''#####'' represents season opening at t=7.

The principle of FSD is demonstrated in Figure 6. The probability distribution function for two alternative actions is shown in the upper panel, and the cumulative probability distribution is shown in the lower panel. The distribution for action A is represented by "****" and that for action B is represented by "####". A dominates B by FSD since the payoffs for A are higher at every cumulative probability level. (In other words, the cumulative probability distribution curve for A is to the <u>right</u> of--or occasionally coincident to--that for B over the entire range of payoffs.) In this case, all individuals would prefer action A to action B. If the cumulative probability distributions were to cross over, as shown in Figure 7, then the test for FSD fails.

The principle of SSD is demonstrated in Figure 7. Two different probability distributions are contrasted; "****" represents action C and "####" represents action D. Since the cumulative probability distributions intersect, the FSD test fails. Up to the point where they cross over, action C would be preferred to action D because of the higher payoffs at each probability level. But to the right of the cross-over, the situation is reversed and action D results in higher payoffs.

The test for SSD essentially determines whether the decision maker would trade the gain in payoffs at the low end for the loss at the high end if he selected action C. To determine this, the cumulative area under the cumulative probability distribution is compared for the two actions. As the theorem states, if the cumulative area for C is consistently less than (or, at some points, equal to) the cumulative area for action D, then action C will dominate by SSD. This is the situation demonstrated in Figure 7, as shown in the bottom panel. All risk-averse individuals would prefer action C to action D because payoffs for action C are not only higher than those for action D at the lower payoffs, but they are high enough to offset the possibility of losses at the high end of the payoff scale. Action D could <u>never</u> dominate action C, however, because of the potential for losses at the low payoffs. Whereas some risk-averse decision makers would be willing to make the tradeoff, there are always some who would not.

The calculations needed to establish FSD or SSD can be time-consuming when there are several actions to compare or several states of the world. The following three corollaries of Theorems 1 and 2 are helpful in reducing the number of comparisons:

Corollary 1: FSD implies SSD.

Corallary 2: The dominating action cannot have the lowest payoff.

Corallary 3: The dominating action must have a higher expected payoff.

The first two corollaries are readily apparent from Figures 6 and 7. The proof for the last corollary is in Anderson (1974). In the event that the two distributions have the same lowest payoff with the same probability (as is the case in the example below), Corollary 2 extends to the next-to-the-lowest payoff.

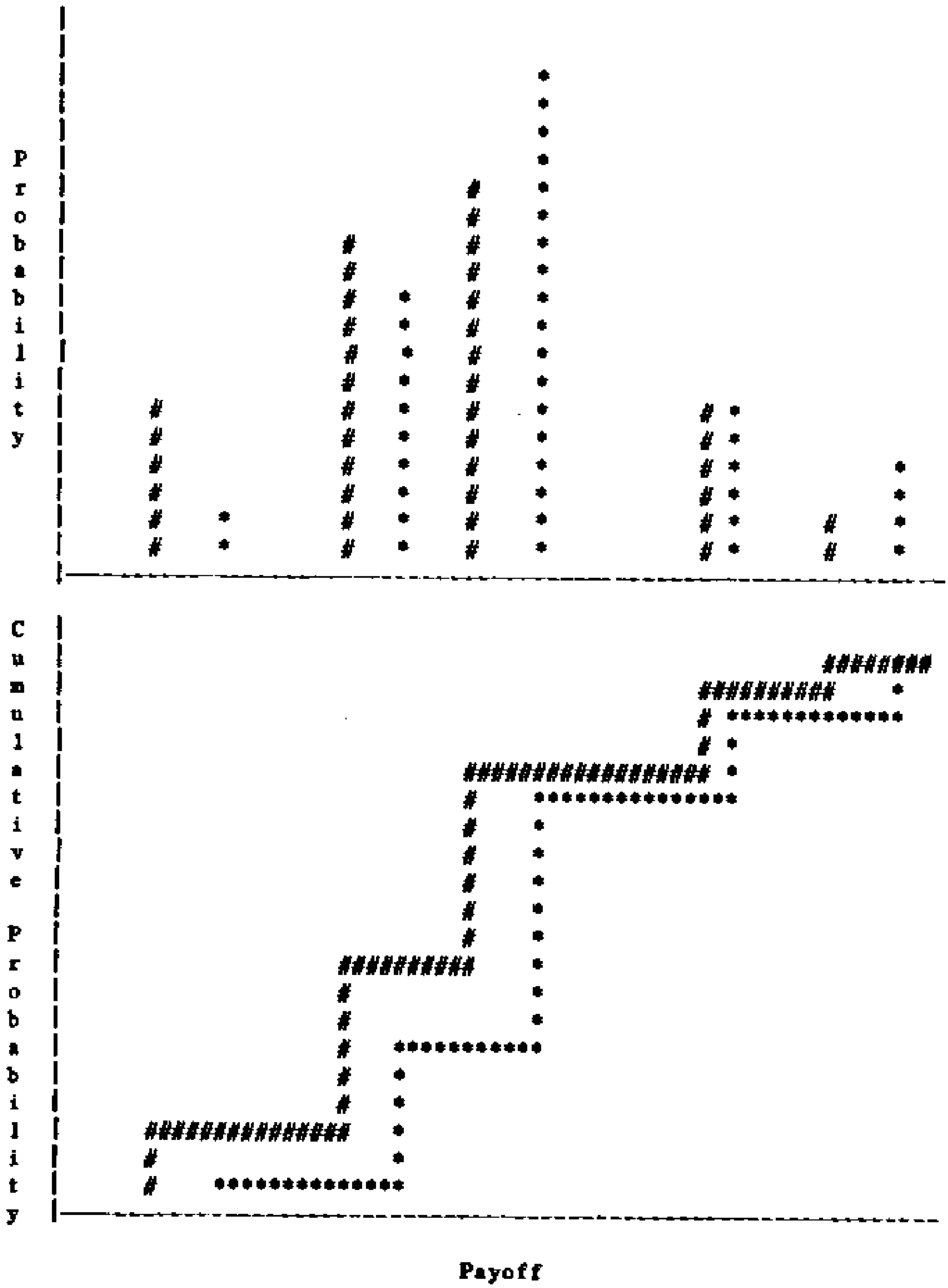


Figure 6. Graphic example of first degree stochastic dominance. Distributions for action A are represented by "***" and those for action B are represented by "###". The distribution for action A dominates B by FSD.

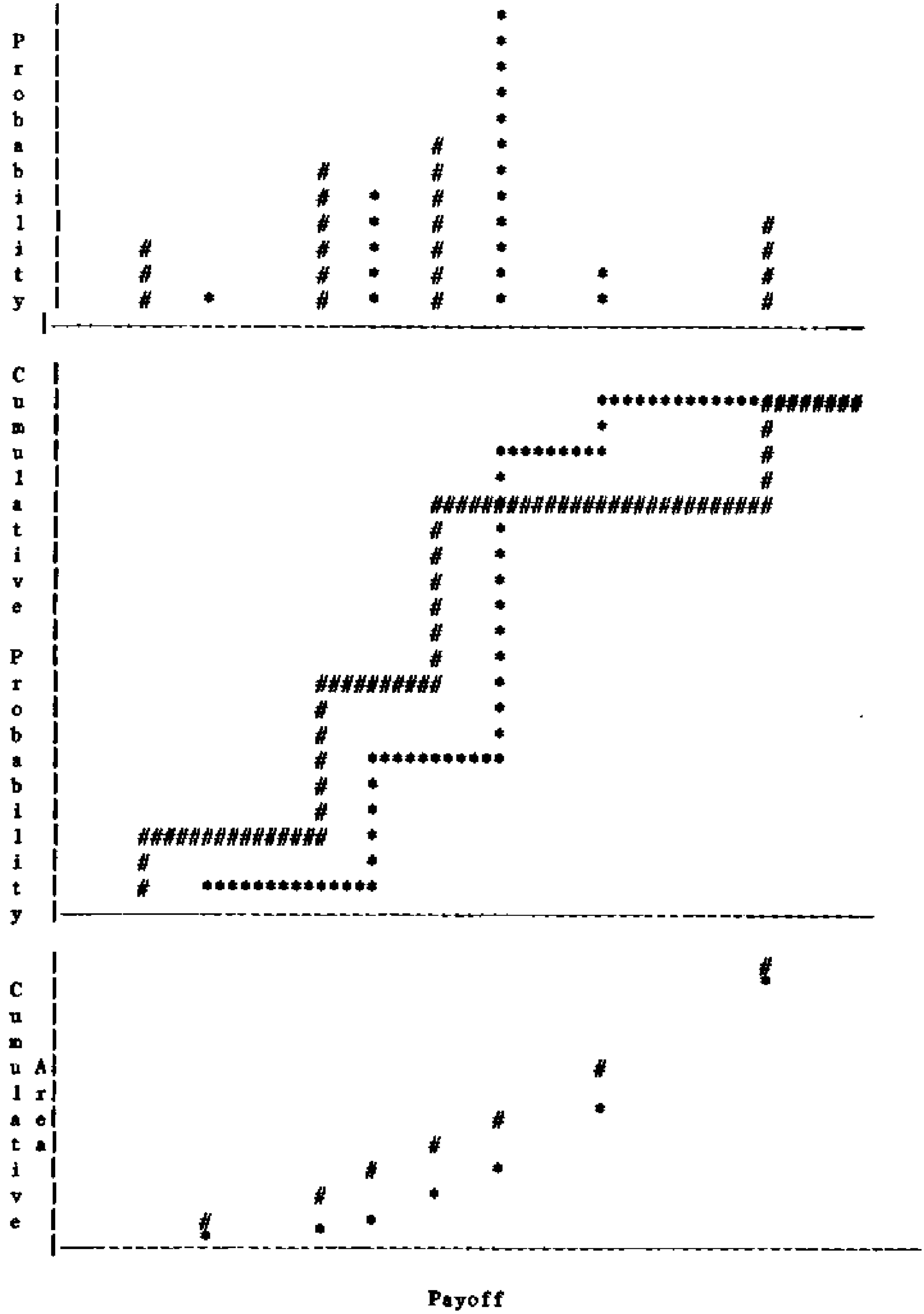


Figure 7. Graphic example of second degree stochastic dominance. Distributions for action C are represented by "***" and those for action D are represented by "###". The distribution for action C dominates D by SSD.

Applying these corollaries to the bay scallop problem, there is only one test possible: Does t=5 dominate t=4? By corollary 3, no action can dominate t=5 since it has the highest expected value. And since t=4 has a lower minimum payoff, there is the possibility that t=5 can dominate t=4 by FSD or SSD. The lowest payoff and its probability are the same for t=5, t=6, and t=7. Since the next-to-the-lowest payoff for t=5 is lower than that for t=6 and t=7, it could not dominate those actions. Similarly, the next-to-the-lowest payoff for t=6 is less than that for t=7, preventing that comparison. But because t=7 has the lowest expected value, it cannot dominate any of the others.

The probability distributions, cumulative probability distributions, and cumulative area under the cumulative probability distributions are contrasted for t=4 and t=5 in Table 6. Comparing the cumulative probability distributions, that for t=5 is less than that for t=4 at all but one payoff (indicated in Table 6-2 by an asterisk), causing the test for FSD to fail. However, the test for SSD passed. The cumulative area for t=4 was greater than that for t=5, indicating that t=5 dominates by SSD. Consequently, the option to open the season at t=4 can be discarded, leaving t=5, t=6 and t=7 as feasible alternatives.

One weakness of the stochastic dominance approach is its emphasis on the low end of the payoff scale. For example, it could not be demonstrated that t=7 was dominated by any of the other actions, even though it had a much lower expected value and most of the distribution was clearly associated with lower payoffs. This occurred because t=7 was "better" at only one point--the lowest non-zero payoff (indicated by an asterisk in Table 7). Furthermore, the difference between the payoffs at this point was only 29 dollars. Only an extremely risk-averse individual would be unwilling to trade this gain for the substantial increase in payoffs that would occur for t=6 at all other states of the world. Nonetheless, the regulator could still discard t=7 from the set of regulatory options, rationalizing that only a very small minority would object. Thus, this analysis can provide insight for use in making subjective selections.

At this point, the fishery manager must select one of the remaining options on the basis of other factors not included in the problem formulation. For example, the potential for natural mortality to occur due to catastrophic events (such as hurricanes or severe cold) always exists, but is difficult to define and include in the equation of motion. Another important factor that is difficult to model is the effects of inclimate weather on effort levels. High winds and sometimes ice and snow can prevent fishermen from scalloping. Accounting for these factors subjectively would favor opening the season on one of the earlier alternative opening dates. Also, political realities may influence the decision.

But even though a single "best" solution cannot usually be obtained using the combined tools of optimal control theory and stochastic dominance, the options facing the fishery manager can be reduced. Perhaps most important, <u>the fishery manager has a quantitative basis on which to make and defend his decision</u>.

Table 6. Distributions for two alternative season openings for bay scallops--t=5 versus t=4--for use with stochastic dominance rules.

| Payoff | Probability distributions | | Cumulative probability distributions | | Cumulative area[a] | | |
|---|---|---|---|---|---|---|---|
| | t=4 | t=5 | t=4 | t=5 | t=4 | t=5 | t=4 minus t=5[b] |
| -403 | .025 | 0 | 0.025 | 0 | 0 | 0 | 0 |
| 0 | .062 | .062 | 0.087 | 0.062 | 10 | 0 | 10 |
| 1983 | .049 | 0 | 0.136 | 0.062 | 183 | 123 | 60 |
| 2460 | 0 | .025 | 0.136 | 0.087 | 247 | 153 | 95 |
| 4052 | .037 | 0 | 0.173 | 0.087 | 464 | 291 | 173 |
| 5753 | 0 | .049 | 0.173 | 0.136 | 758 | 439 | 319 |
| 8866 | 0 | .037 | 0.173 | 0.173 | 1297 | 862 | 434 |
| 12025 | .049 | 0 | 0.222 | 0.173 | 1843 | 1409 | 434 |
| 14895 | 0 | .049 | 0.222 | 0.222 | 2480 | 1905 | 575 |
| 21175 | .074 | 0 | 0.296 | 0.222 | 3875 | 3300 | 575 |
| 22893 | .025 | 0 | 0.321 | 0.222 | 4383 | 3681 | 702 |
| 25036 | 0 | .074 | 0.321 | 0.296 | 5071 | 4157 | 914 |
| 26919 | .049 | 0 | 0.370 | 0.296 | 5675 | 4714 | 961 |
| 28110 | 0 | .025 | 0.370 | 0.321 | 6116 | 5067 | 1050 |
| 30165 | 0 | .049 | 0.370 | 0.370 | 6877 | 5726 | 1150 |
| 46594 | .049 | 0 | 0.419 | 0.370 | 12955 | 11805 | 1150 |
| 47180 | .012 | 0 | 0.431 | 0.370 | 13201 | 12022 | 1179 |
| 49510 | 0 | .049 | 0.431 | 0.419 | 14205 | 12884 | 1321 |
| 51637 | .099 | 0 | 0.530 | 0.419 | 15122 | 13775 | 1347 |
| 51870 | 0 | .012 | 0.530 | 0.431 | 15245 | 13873 | 1372 |
| 53920 | 0 | .099 | 0.530 | 0.530 | 16332 | 14756 | 1575 |
| 68376 | .074 | 0 | 0.604 | 0.530 | 23993 | 22418 | 1575 |
| 71919 | 0 | .074 | 0.604 | 0.604 | 26133 | 24296 | 1838 |
| 74936 | .025 | 0 | 0.629 | 0.604 | 27956 | 26118 | 1838 |
| 77237 | 0 | .025 | 0.629 | 0.629 | 29403 | 27508 | 1895 |
| 100642 | .148 | 0 | 0.777 | 0.629 | 44125 | 42230 | 1895 |
| 101736 | 0 | .148 | 0.777 | 0.777 | 44975 | 42918 | 2057 |
| 117791 | .049 | 0 | 0.826 | 0.777 | 57449 | 55392 | 2057 |
| 119718 | 0 | .049 | 0.826 | 0.826 | 59041 | 56890 | 2151 |
| 151419 | 0 | .099 | 0.826 | 0.925* | 85226 | 83075 | 2151 |
| 154969 | .099 | 0 | 0.925 | 0.925 | 88159 | 86358 | 1800 |
| 170996 | .025 | 0 | 0.950 | 0.925 | 102983 | 101183 | 1800 |
| 171734 | 0 | .025 | 0.950 | 0.950 | 103685 | 101866 | 1818 |
| 201102 | .049 | 0 | 0.999 | 0.950 | 131584 | 129766 | 1818 |
| 212422 | 0 | .049 | 0.999 | 0.999 | 142893 | 140520 | 2373 |

[a]Cumulative area under the cumulative probability distribution.
[b]Since this difference is positive for each payoff, t=5 is stochastically dominant.

Table 7. Distributions for two alternative season openings for bay scallops—t=6 versus t=7—for use with stochastic dominance rules.

| | Probability distributions | | Cumulative probability distributions | | Cumulative area[a] | | |
|---|---|---|---|---|---|---|---|
| Payoff | t=6 | t=7 | t=6 | t=7 | t=6 | t=7 | t=7 minus t=6[b] |
| 0 | .062 | .062 | 0.062 | 0.062 | 0.0 | 0.0 | 0 |
| 3789 | .025 | 0 | 0.087* | 0.062 | 234.9 | 234.9 | 0 |
| 3818 | 0 | .025 | 0.087 | 0.087 | 237.4 | 236.7 | -1 |
| 4781 | 0 | .049 | 0.087 | 0.136 | 321.2 | 320.5 | -1 |
| 6613 | 0 | .037 | 0.087 | 0.173 | 480.6 | 569.6 | 89 |
| 6829 | .049 | 0 | 0.136 | 0.173 | 499.4 | 607.0 | 108 |
| 7918 | 0 | .049 | 0.136 | 0.222 | 647.5 | 795.4 | 148 |
| 10239 | .037 | 0 | 0.173 | 0.222 | 963.2 | 1310.7 | 348 |
| 11150 | 0 | .074 | 0.173 | 0.296 | 1120.8 | 1512.9 | 392 |
| 12982 | 0 | .025 | 0.173 | 0.321 | 1437.7 | 2055.2 | 617 |
| 13406 | 0 | .049 | 0.173 | 0.380 | 1511.0 | 2191.3 | 680 |
| 15474 | .049 | 0 | 0.222 | 0.380 | 1868.8 | 2977.1 | 1108 |
| 17519 | 0 | .049 | 0.222 | 0.429 | 2322.8 | 3754.2 | 1431 |
| 17943 | 0 | .099 | 0.222 | 0.528 | 2416.9 | 3936.1 | 1519 |
| 19351 | 0 | .012 | 0.222 | 0.540 | 2729.5 | 4679.6 | 1950 |
| 23432 | 0 | .074 | 0.222 | 0.614 | 3635.5 | 6883.3 | 3248 |
| 23888 | 0 | .025 | 0.222 | 0.639 | 3736.7 | 7163.3 | 3427 |
| 25276 | .074 | 0 | 0.296 | 0.639 | 4044.9 | 8050.2 | 4005 |
| 27969 | 0 | .148 | 0.296 | 0.787 | 4842.0 | 9771.0 | 4929 |
| 28406 | .025 | 0 | 0.321 | 0.787 | 4971.3 | 10115.0 | 5144 |
| 31065 | .049 | 0 | 0.370 | 0.787 | 5824.9 | 12207.6 | 6383 |
| 33457 | 0 | .049 | 0.370 | 0.836 | 6709.9 | 14090.1 | 7380 |
| 37994 | 0 | .099 | 0.370 | 0.935 | 8388.6 | 17883.0 | 9494 |
| 43483 | 0 | .025 | 0.370 | 0.950 | 10419.5 | 23015.2 | 12596 |
| 44280 | .012 | 0 | 0.382 | 0.950 | 10714.4 | 23772.4 | 13058 |
| 46537 | .049 | 0 | 0.431 | 0.950 | 11576.6 | 25916.5 | 14340 |
| 48020 | 0 | .049 | 0.431 | 0.999 | 12215.8 | 27325.4 | 15110 |
| 49197 | .099 | 0 | 0.530 | 0.999 | 12723.1 | 28501.2 | 15778 |
| 64877 | .074 | 0 | 0.604 | 0.999 | 21033.5 | 44165.5 | 23132 |
| 67799 | .025 | 0 | 0.629 | 0.999 | 22798.3 | 47084.6 | 24286 |
| 83008 | .148 | 0 | 0.777 | 0.999 | 32364.8 | 62278.4 | 29914 |
| 98689 | .049 | 0 | 0.826 | 0.999 | 44548.9 | 77943.7 | 33395 |
| 116820 | .099 | 0 | 0.925 | 0.999 | 59525.2 | 96056.6 | 36531 |
| 132500 | .025 | 0 | 0.950 | 0.999 | 74029.2 | 111720.9 | 37692 |
| 150632 | .049 | 0 | 0.999 | 0.999 | 91254.6 | 129834.8 | 38580 |

[a]Cumulative area under the cumulative probability distribution.
[b]Since this difference is negative at two points, t=6 is not stochastically dominant.

# CHAPTER 5. SUMMARY AND CONCLUSIONS

A bioeconomic optimal control model was constructed for the bay scallop fishery to determine the optimal season opening/closing schedule. Quotas were not imposed in the model, nor were there restrictions on the number of fishing days allowed per week. Other regulations in current practice in North Carolina were maintained. 120 separate scenarios were created using two price estimates, two cost estimates, five population size estimates, three estimates of the catchability coefficient and two effort levels. Four possibilities for the optimal time to open the season resulted, ranging from the second week in January to the first week in February. Applying stochastic dominance to a subset of these solutions using a set of hypothetical probabilities for the states of the world reduced the alternative opening season dates to three. The current practice of opening the season in early December was sub-optimal for all scenarios.

The corresponding season for the unregulated case was also determined for each of the 120 input combinations. The unregulated case represents the time when it is profitable to harvest scallops under the assumptions of the model but with the opportunity cost of harvesting set equal to zero. Season openings ranged from the first week of December to the last week of January. The optimal solution with regulation was typically two-three weeks later than the solution for the unregulated case. Delaying the season opening substantially increased the present value of the harvest for all comparisons.

The results of this analysis clearly suggest that gains can be obtained by delaying the opening season for bay scallops beyond the traditional December opening. The size of the gain depends on prices, costs, population sizes and other variables. Gains also come from eliminating the quota and daily fishing restrictions. The basic principle behind optimal harvesting of a resource through time is to delay harvesting only until the increase in value of the resource is no longer greater than the return that could be obtained by harvesting the resource and investing the proceeds elsewhere. For an annual fishery such as the North Carolina bay scallop fishery, the optimal harvest strategy would be to apply as much fishing effort to the fishery as possible (and still maintain profitability to each unit of effort) once the optimal time to harvest has arrived. The restrictions on catch and effort are inherently inconsistent with this optimal harvesting strategy.

While this analysis provides useful insight into the problem of when to open the bay scallop season, there are several aspects of the model that should be further developed before the model can be routinely used to predict the season opening. The assumption of a constant effort level throughout the entire harvest season is perhaps the most implausible aspect of the model. As discussed earlier, fishing effort is a function of expected profit, which in turn depends upon costs, market price and the density of the scallop beds. In addition, effort in the first few weeks of the season is greater because of participation by part-timers who stop fishing when the weather gets colder and the population becomes less dense. In order for the model to be responsive to these factors, a supply function for effort needs to be developed in a manner similar to that used by Kellogg (1985) for the New

River shrimp fishery. At the time of this study, sufficent data for such a function did not exist, and only ad hoc estimates of fishing effort could be used. (See Section 3.5 for recommendations on further research needs.)

Another oversimplification embodied in the model is the assumption of zero natural mortality during the harvest season. The effect of non-zero natural mortality on the solution would be an earlier season opening than predicted here. (Some insight into the effects of non-zero natural mortality can be obtained by comparing the effects of different levels of fishing mortality (see Appendix B) on the opening date.) Incorporation of a natural mortality coefficient in the equation of motion would be a useful refinement to the model, but this refinement must await the availability of a suitable mortality estimate.

Bioeconomic optimal control models are not the only input that should be used by the fishery manager in promulgating regulations. Some aspects of a fishery are not easily incorporated into a model, such as income re-distribution, political realities, dynamics of ecosystems, and catastrophic weather events. But management models can provide important insights that cannot be obtained in any other way. For example, it would be difficult to evaluate the cost effectiveness of a proposed regulation without use of a management model. The example presented in this study should be useful as a guide for development of management models for other fisheries.

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## APPENDIX A: SOLUTION ALGORITHM FOR THE BAY SCALLOP HARVESTING PROBLEM

The following program is written in IBM-PC Basic.

```
10 REM  BAY SCALLOP PROGRAM
20 REM
30 REM FUNCTIONS USED IN THE PROGRAM
40 REM
50 DEF FNCUMTEMP(T)=20.203*(T+4.3)-1.012*(T+4.3)^2
   +.027*(T+4.3)^3
60 DEF FNSHELLS(CT,T)=6.378*(1-EXP(.0298*(T+4.3)-.0065*CT))
   +5.9*EXP(.0298*(T+4.3)-.0065*CT)
70 DEF FNMAX(SHELLS)=.027*SHELLS^3
80 DEF FNB(CT,T)=-.4415*(T+4.3)+.0969*CT-.0034*(CT^2)/(T+4.3)
90 DEF FNMEAT(MAX,B)=.002205*(MAX*(1-EXP(-B))+2.522*EXP(-B))
100 DEF FNDISCOUNT(T)=EXP(-.001827*T)
110 DEF FNPRICE(T)=-4.24904127#+4.73008E-03*INCOME
    -1.85448147#*SEAP+.56224238#*SEAP1+1.69072116#*SEAP2
    -.0000054761407#*CALQ+.38661194#*T-4.133764E-02*(T^2)
    +1.19521E-03*(T^3)
120 U$="## ####### # #.###### ######### ######## ##.####
    ###### .##### ######### #########"
130 REM
140 REM INITIALIZING VARIABLES AND SETTING CONSTANTS
150 REM
160 X0=23000000 'VALUES USED ARE 13, 18, 23, 28 AND 33 MIL.
170 X=X0
180 Q=.0002 'VALUES USED ARE .0001, .0002 AND .0003
190 QPRINT=Q
200 REM  SEE LINE 990 AND 770 WHERE Q IS ALSO INITIALIZED
210 E=540    'VALUES USED ARE 540 AND 750
220 LIMIT=50*435          'CHANGE "50" TO QUOTA IF DESIRED
230 CUMPV=0:  CUMHARV=0
240 COST=42.55            'VALUES USED ARE 42.55 AND 34.04
260 REM EXOGENOUS VARIABLES FOR THE PRICE FUNCTION
270 REM              VALUES USED ARE:    1980-81       1981-82
280 REM                                 ----------   -----------
300 SEAP=2!        '                          2.00          1.31
310 SEAP1=2!       '                          2.00          1.31
320 SEAP2=2!       '                          2.00          1.31
330 CALQ=531369!   '                       531,369     1,084,457
340 INCOME=882     '                           882           887
360 REM
363 PRINT "COST=";COST;"SEAP=";SEAP;"E=";E;"Q=";Q;"X=";X
370 INPUT "INITIAL VALUE FOR LAMBDA";LAMBDA
380 REM
420 PRINT " T" TAB(4) "SWITCH" TAB(11) "PHI" TAB(16) "LAMBDA"
    TAB(26) "X" TAB(32) "HARVEST" TAB(41) "PRICEPER" TAB(53)
    "PV" TAB(58) "Q" TAB(65) "CUMPV" TAB(72) "CUMHARV"
430 REM
440 REM THE MAIN PROGRAM
450 REM
460 FOR T=0 TO 17
470 XPRINT=X
```

```
480 LAMPRINT=LAMBDA
490 IF Q*X>LIMIT THEN Q=LIMIT/X 'CORRECTS Q WHEN LIMIT BINDS
500 PRICE=FNPRICE(T)
510 DISCOUNT=FNDISCOUNT(T)
520 REM
530 REM CALCULATION OF MEAT SIZE AT TIME T
540 REM
550 CT=FNCUMTEMP(T)
560 SHELLS=FNSHELLS(CT,T)
570 MAX=FNMAX(SHELLS)
580 B=FNB(CT,T)
590 MEAT=FNMEAT(MAX,B)
600 PRICEPER=PRICE*MEAT
610 REM
620 REM CHECK TO SEE IF SEASON SHOULD OPEN THIS WEEK
630 REM
640 SWITCH=(PRICE*MEAT*E*Q*X-COST*E)*DISCOUNT-LAMBDA*E*Q*X
650 REM
660 IF SWITCH<0 THEN PHI=0
670 IF SWITCH>0 THEN PHI=1
680 IF SWITCH<0 THEN PV=0
690 IF SWITCH<0 THEN HARVEST=0
700 IF PHI=0 THEN GOTO 1410
710 REM
720 REM CALCULATION OF NEXT X AND LAMBDA IF SEASON IS OPEN
730 REM CALCULATES PRESENT VALUE AND HARVEST FOR THE WEEK
750 HARVEST=0:  PV=0
760 FOR N=1 TO 10
770    Q=.0002
780    IF Q*X>LIMIT THEN Q=LIMIT/X 'ADJUSTS Q IF LIMIT BINDS
790    IF Q*X>LIMIT THEN QPRINT=LIMIT/X 'DETECTS Q CONSTRAINT
795    H=.1
800 REM CALCULATION OF PV AND HARVEST
810 REM HOLDS MEAT SIZE, PRICE, AND DISCOUNT CONSTANT
    FOR THE WEEK
820    SUBHARV=H*Q*E*X
830    SUBPV=H*(PRICE*MEAT*E*Q*X-COST*E)*DISCOUNT
840    HARVEST=HARVEST+SUBHARV
850    PV=PV+SUBPV
860 REM CALCULATION OF X-DOT WITH RUNGE-KUTTA
870    K0X=-E*Q*X
880    K1X=-E*Q*(X+.5*H*K0X)
890    K2X=-E*Q*(X+.5*H*K1X)
900    K3X=-E*Q*(X+H*K2X)
910    X=X+(H/6)*(K0X+2*K1X+2*K2X+K3X)
930 NEXT N
940 REM
950 REM CALCULATION OF LAMBDA-DOT WITH RUNGE-KUTTA
960 REM ALLOWS DISCOUNT, PRICE AND MEAT SIZE TO CHANGE
    WITH EACH ITERATION
970 REM HOLDS Q CONSTANT AND EQUAL TO Q AT TIME T
980 REM
990 Q=.0002                  'RE-SETS Q TO Q AT TIME T
```

```
1000 IF Q*XPRINT>LIMIT THEN Q=LIMIT/XPRINT
1010 REM
1020 FOR J=1 TO 10
1030        H=.1
1040        RT=T+(J-1)*H    'RT STANDS FOR REAL TIME IN WEEKS
1050 REM
1060 REM CALCULATION OF K0
1070 REM
1080        K0L=E*Q*LAMBDA-PRICE*MEAT*Q*E*DISCOUNT
1090 REM
1100 REM CALCULATION OF K1 AND K2
1110 REM
1120        DISCOUNT=FNDISCOUNT(RT+.5*H)
1130        CT=FNCUMTEMP(RT+.5*H)
1140        SHELLS=FNSHELLS(CT,RT+.5*H)
1150        MAX=FNMAX(SHELLS)
1160        B=FNB(CT,RT+.5*H)
1170        MEAT=FNMEAT(MAX,B)
1180        PRICE=FNPRICE(RT+.5*H)
1190 REM
1200      K1L=E*Q*(LAMBDA+.5*H*K0L)-PRICE*MEAT*Q*E*DISCOUNT
1210      K2L=E*Q*(LAMBDA+.5*H*K1L)-PRICE*MEAT*Q*E*DISCOUNT
1220 REM
1230 REM CALCULATION OF K3
1240 REM
1250        DISCOUNT=FNDISCOUNT(RT+H)
1260        CT=FNCUMTEMP(RT+H)
1270        SHELLS=FNSHELLS(CT,RT+H)
1280        MAX=FNMAX(SHELLS)
1290        B=FNB(CT,RT+H)
1300        MEAT=FNMEAT(MAX,B)
1310        PRICE=FNPRICE(RT+H)
1320 REM
1330        K3L=E*Q*(LAMBDA+H*K2L)-PRICE*MEAT*Q*E*DISCOUNT
1340 REM
1350 REM CALCULATION OF LAMBDA
1360 REM
1370        LAMBDA=LAMBDA+(H/6)*(K0L+2*K1L+2*K2L+K3L)
1380 NEXT J
1390 IF LAMBDA<0 THEN LAMBDA=0 'THIS KEEPS LAMBDA POSITIVE
1400 REM
1410 CUMPV=CUMPV+PV     'CALCULATION OF CUM. PRESENT VALUE
1420 CUMHARV=CUMHARV+HARVEST  'CALCULATION OF CUM. HARVEST
1430 PRINT USING U$;T,SWITCH,PHI,LAMPRINT,XPRINT,HARVEST,
     PRICEPER,PV,QPRINT,CUMPV,CUMHARV
1440 NEXT T
1445 PERCENT=CUMHARV/X0
1446 PRINT "percent=";PERCENT
1450 END
```

# APPENDIX B: OPTIMAL SOLUTIONS TO THE BAY SCALLOP HARVESTING PROBLEM

Table B1. Summary of optimal harvesting solutions for 120 combinations of exogenous variables. Present value, cost, and λ are in units of 1967 dollars.

| | | | Boat-days per week = 540 | | | | Boat-days per week = 750 | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| $x_0$ (millions) | Cost | Price[a] | Optimal season[b] | Optimal λ | Total present value | Percent of stock harvested | Optimal season[b] | Optimal λ | Total present value | Percent of stock harvested |
| | | | | | q = 0.0001 | | | | | |
| 13 | 42.55 | low | none | -- | --- | -- | none | -- | --- | -- |
| 18 | 42.55 | low | none | -- | --- | -- | none | -- | --- | -- |
| 23 | 42.55 | low | none | -- | --- | -- | none | -- | --- | -- |
| 28 | 42.55 | low | none | -- | --- | -- | none | -- | --- | -- |
| 33 | 42.55 | low | none | -- | --- | -- | none | -- | --- | -- |
| 13 | 34.04 | low | none | -- | --- | -- | none | -- | --- | -- |
| 18 | 34.04 | low | none | -- | --- | -- | none | -- | --- | -- |
| 23 | 34.04 | low | none | -- | --- | -- | none | -- | --- | -- |
| 28 | 34.04 | low | 7 | 0.0003 | 118 | 5 | none | -- | --- | -- |
| 33 | 34.04 | low | 6-8 | 0.0014 | 6,084 | 15 | 6-7 | 0.0020 | 6,335 | 14 |
| 13 | 42.55 | high | none | -- | --- | -- | none | -- | --- | -- |
| 18 | 42.55 | high | none | -- | --- | -- | none | -- | --- | -- |
| 23 | 42.55 | high | 7 | 0.0010 | 932 | 5 | 7 | 0.0010 | 990 | 7 |
| 28 | 42.55 | high | 6-9 | 0.0036 | 13,838 | 19 | 6-8 | 0.0036 | 14,932 | 20 |
| 33 | 42.55 | high | 5-10 | 0.0044 | 36,439 | 28 | 5-9 | 0.0048 | 39,457 | 31 |
| 13 | 34.04 | high | none | -- | --- | -- | none | -- | --- | -- |
| 18 | 34.04 | high | 7 | 0.0006 | 335 | 5 | 7 | 0.0007 | 227 | 7 |
| 23 | 34.04 | high | 6-9 | 0.0039 | 13,309 | 19 | 6-8 | 0.0042 | 14,291 | 20 |
| 28 | 34.04 | high | 5-10 | 0.0054 | 37,511 | 28 | 5-9 | 0.0062 | 41,117 | 31 |
| 33 | 34.04 | high | 4-11 | 0.0065 | 67,695 | 35 | 5-11 | 0.0070 | 75,433 | 41 |

Table B1. (continued)

| $x_e$ (millions) | Cost | Price[a] | Boat-days per week = 540: Optimal season[b] | Optimal λ | Total present value | Percent of stock harvested | Boat-days per week = 750: Optimal season[b] | Optimal λ | Total present value | Percent of stock harvested |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | q = 0.0002 | | | | | |
| 13 | 42.55 | low | none | -- | --- | -- | none | -- | --- | -- |
| 18 | 42.55 | low | none | -- | --- | -- | none | -- | --- | -- |
| 23 | 42.55 | low | 6-8 | 0.0025 | 10,239 | 28 | 6-7 | 0.0025 | 10,841 | 26 |
| 28 | 42.55 | low | 5-8 | 0.0030 | 28,110 | 35 | 6-8 | 0.0045 | 30,568 | 36 |
| 33 | 42.55 | low | 5-9 | 0.0040 | 51,870 | 42 | 5-8 | 0.0050 | 54,382 | 45 |
| 13 | 34.04 | low | none | -- | --- | -- | none | -- | --- | -- |
| 18 | 34.04 | low | 6-8 | 0.0025 | 6,829 | 28 | 6-7 | 0.0025 | 7,387 | 26 |
| 23 | 34.04 | low | 6-9 | 0.0043 | 25,276 | 35 | 6-8 | 0.0045 | 27,135 | 36 |
| 28 | 34.04 | low | 5-9 | 0.0052 | 49,510 | 42 | 6-9 | 0.0056 | 52,906 | 45 |
| 33 | 34.04 | low | 5-10 | 0.0060 | 77,237 | 48 | 5-9 | 0.0060 | 83,457 | 53 |
| 13 | 42.55 | high | 7-8 | 0.0031 | 3,818 | 20 | 7 | 0.0033 | 4,034 | 14 |
| 18 | 42.55 | high | 6-9 | 0.0070 | 31,065 | 35 | 6-8 | 0.0074 | 32,510 | 36 |
| 23 | 42.55 | high | 5-10 | 0.0085 | 71,919 | 48 | 5-9 | 0.0090 | 74,918 | 53 |
| 28 | 42.55 | high | 5-11 | 0.0100 | 119,718 | 53 | 5-10 | 0.0100 | 126,986 | 60 |
| 33 | 42.55 | high | 5-12 | 0.0108 | 171,734 | 58 | 5-11 | 0.0110 | 183,488 | 65 |
| 13 | 34.04 | high | 6-8 | 0.0060 | 15,474 | 28 | 6-8 | 0.0063 | 16,128 | 37 |
| 18 | 34.04 | high | 5-10 | 0.0080 | 53,920 | 48 | 6-9 | 0.0095 | 56,248 | 45 |
| 23 | 34.04 | high | 5-11 | 0.0100 | 101,736 | 53 | 5-10 | 0.0110 | 108,357 | 60 |
| 28 | 34.04 | high | 4-12 | 0.0110 | 154,969 | 63 | 5-10 | 0.0120 | 164,760 | 60 |
| 33 | 34.04 | high | 4-13 | 0.0115 | 212,422 | 66 | 5-12 | 0.0122 | 227,755 | 70 |

Table B2. (continued)

| $x_0$ (millions) | Cost | Price[a] | Boat-days per week = 540 | | | | Boat-days per week = 750 | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Optimal season[b] | Optimal λ | Total present value | Percent of stock harvested | Optimal season[b] | Optimal λ | Total present value | Percent of stock harvested |
| | | | | | q = 0.0003 | | | | | |
| 13 | 42.55 | low | 7 | 0.0015 | 1,573 | 15 | 7 | 0.0015 | 1,276 | 20 |
| 18 | 42.55 | low | 6-8 | 0.0038 | 17,418 | 40 | 6-7 | 0.0040 | 18,090 | 37 |
| 23 | 42.55 | low | 6-9 | 0.0055 | 42,861 | 48 | 6-8 | 0.0060 | 45,224 | 50 |
| 28 | 42.55 | low | 5-9 | 0.0057 | 73,701 | 56 | 6-9 | 0.0066 | 77,309 | 60 |
| 33 | 42.55 | low | 5-10 | 0.0066 | 107,737 | 63 | 6-9 | 0.0075 | 113,599 | 60 |
| 13 | 34.04 | low | 6-7 | 0.0036 | 8,304 | 28 | 6-7 | 0.0030 | 8,159 | 37 |
| 18 | 34.04 | low | 6-9 | 0.0054 | 31,967 | 48 | 6-8 | 0.0055 | 33,749 | 50 |
| 23 | 34.04 | low | 5-9 | 0.0057 | 62,970 | 56 | 6-9 | 0.0068 | 66,202 | 60 |
| 28 | 34.04 | low | 5-10 | 0.0067 | 98,006 | 63 | 6-9 | 0.0076 | 102,492 | 60 |
| 33 | 34.04 | low | 5-10 | 0.0075 | 134,934 | 63 | 5-9 | 0.0081 | 143,099 | 68 |
| 13 | 42.55 | high | 6-8 | 0.0082 | 29,457 | 39 | 6-8 | 0.0084 | 30,222 | 50 |
| 18 | 42.55 | high | 5-9 | 0.01071 | 78,080 | 56 | 6-9 | 0.0110 | 81,527 | 60 |
| 23 | 42.55 | high | 5-10 | 0.0120 | 136,033 | 63 | 5-9 | 0.0124 | 140,959 | 68 |
| 28 | 42.55 | high | 5-11 | 0.0127 | 199,263 | 68 | 5-10 | 0.0135 | 207,314 | 75 |
| 33 | 42.55 | high | 5-12 | 0.0131 | 265,578 | 73 | 5-10 | 0.0142 | 278,061 | 75 |
| 13 | 34.04 | high | 5-9 | 0.0090 | 47,569 | 56 | 6-8 | 0.0106 | 49,126 | 50 |
| 18 | 34.04 | high | 5-10 | 0.0119 | 104,096 | 63 | 5-9 | 0.0112 | 107,576 | 68 |
| 23 | 34.04 | high | 5-11 | 0.0129 | 167,077 | 68 | 5-10 | 0.0128 | 174,341 | 75 |
| 28 | 34.04 | high | 5-12 | 0.0134 | 234,114 | 73 | 5-10 | 0.0144 | 245,088 | 75 |
| 33 | 34.04 | high | 5-13 | 0.0138 | 303,550 | 77 | 5-11 | 0.0148 | 319,861 | 80 |

[a]The "high" price was produced by solving the price equation using the 1980-81 average of the exogenous variables (sea scallop price, callico scallop landings, and income). The "low" price was produced using the 1981-82 average of these variables.

[b]The optimal season is in weeks where the first week is the first seven days in December. Numbering begins with zero. For example, an optimal season of "5-12" denotes that the season should open at the <u>beginning</u> of the sixth week (delaying the opening five weeks past December 1) and remain open <u>through</u> the thirteenth week.

Table B2. Summary of unregulated[a] harvesting solutions for 120 combinations of exogenous variables. Present value and cost are in units of 1967 dollars.

| | | | Boat-days per week = 540 | | | Boat-days per week = 750 | | |
|---|---|---|---|---|---|---|---|---|
| $x_0$ (millions) | Cost | Price[b] | season[c] | Total present value | Percent of stock harvested | season[c] | Total present value | Percent of stock harvested |
| | | | | q = 0.0001 | | | | |
| 13 | 42.55 | low | none | --- | -- | none | --- | -- |
| 18 | 42.55 | low | none | --- | -- | none | --- | -- |
| 23 | 42.55 | low | none | --- | -- | none | --- | -- |
| 28 | 42.55 | low | none | --- | -- | none | --- | -- |
| 33 | 42.55 | low | none | --- | -- | none | --- | -- |
| 13 | 34.04 | low | none | --- | -- | none | --- | -- |
| 18 | 34.04 | low | none | --- | -- | none | --- | -- |
| 23 | 34.04 | low | none | --- | -- | none | --- | -- |
| 28 | 34.04 | low | 6 | -107[d] | 5 | 6 | -382 | 7 |
| 33 | 34.04 | low | 4-7 | 1,643 | 19 | 4-6 | -293 | 20 |
| 13 | 42.55 | high | none | --- | -- | none | --- | -- |
| 18 | 42.55 | high | none | --- | -- | none | --- | -- |
| 23 | 42.55 | high | 5,7[e] | -614 | 10 | 5 | -713 | 7 |
| 28 | 42.55 | high | 4-8 | 10,408 | 24 | 4-7 | 8,618 | 26 |
| 33 | 42.55 | high | 3-9 | 28,925 | 32 | 3-8 | 25,586 | 36 |
| 13 | 34.04 | high | none | --- | -- | none | --- | -- |
| 18 | 34.04 | high | 6 | 115 | 5 | 6 | -76 | 7 |
| 23 | 34.04 | high | 3-8 | 5,549 | 28 | 3-6 | 2,561 | 26 |
| 28 | 34.04 | high | 2-9 | 23,489 | 35 | 2-8 | 16,951 | 41 |
| 33 | 34.04 | high | 2-11 | 55,442 | 42 | 2-9 | 52,810 | 45 |

Table B2. (continued)

| $x_0$ (millions) | Cost | Price[b] | Boat-days per week = 540 | | | Boat-days per week = 750 | | |
|---|---|---|---|---|---|---|---|---|
| | | | season[c] | Total present value | Percent of stock harvested | season[c] | Total present value | Percent of stock harvested |
| | | | | q = 0.0002 | | | | |
| 13 | 42.55 | low | none | --- | — | none | --- | — |
| 18 | 42.55 | low | 6 | -38 | 10 | 6 | -629 | 14 |
| 23 | 42.55 | low | 4-6 | 4,052 | 28 | 4-5 | 2,125 | 26 |
| 28 | 42.55 | low | 3-7 | 12,453 | 42 | 3-6 | 5,454 | 45 |
| 33 | 42.55 | low | 3-8 | 36,233 | 48 | 3-7 | 28,985 | 53 |
| 13 | 34.04 | low | none | --- | — | none | — | — |
| 18 | 34.04 | low | 4-6 | 1,983 | 28 | 4 | -2,589 | 28 |
| 23 | 34.04 | low | 3-7 | 12,669 | 42 | 3-4 | -7,360 | 48 |
| 28 | 34.04 | low | 3-8 | 37,361 | 48 | 3-5 | -7,928 | 63 |
| 33 | 34.04 | low | 2-9 | 47,036 | 58 | 2-4 | -5,401 | 63 |
| 13 | 42.55 | high | 4-5 | -403 | 20 | 4,6[e] | -1,713 | 26 |
| 18 | 42.55 | high | 2-6 | 7,025 | 42 | 2-5 | -1,595 | 45 |
| 23 | 42.55 | high | 2-8 | 45,999 | 53 | 2-7 | 33,985 | 60 |
| 28 | 42.55 | high | 1-9 | 66,814 | 63 | 1-7 | 46,540 | 65 |
| 33 | 42.55 | high | 1-10 | 115,532 | 66 | 1-8 | 94,145 | 70 |
| 13 | 34.04 | high | 3-6 | 6,376 | 35 | 3-5 | 3,300 | 37 |
| 18 | 34.04 | high | 2-8 | 33,227 | 53 | 2-6 | 25,255 | 53 |
| 23 | 34.04 | high | 1-9 | 59,274 | 63 | 1-7 | 42,982 | 65 |
| 28 | 34.04 | high | 1-10 | 109,056 | 66 | 1-8 | 92,158 | 70 |
| 33 | 34.04 | high | 1-11 | 162,232 | 70 | 1-9 | 145,609 | 75 |

Table B2. (continued)

| $x_0$ (millions) | Cost | Price[b] | Boat-days per week = 540 | | | Boat-days per week = 750 | | |
|---|---|---|---|---|---|---|---|---|
| | | | season[c] | Total present value | Percent of stock harvested | season[c] | Total present value | Percent of stock harvested |
| | | | | q = 0.0003 | | | | |
| 13 | 42.55 | low | 5 | -68 | 15 | 5 | -945 | 20 |
| 18 | 42.55 | low | 3-5 | 746 | 39 | 3-4 | -2,615 | 37 |
| 23 | 42.55 | low | 3-7 | 23,122 | 56 | 3-6 | 14,916 | 60 |
| 28 | 42.55 | low | 2-7 | 29,195 | 63 | 2-5 | 14,939 | 60 |
| 33 | 42.55 | low | 2-8 | 58,883 | 68 | 2-6 | 42,171 | 68 |
| 13 | 34.04 | low | 4-6 | 2,214 | 39 | 4-5 | 1,143 | 37 |
| 18 | 34.04 | low | 3-7 | 16,115 | 56 | 3-6 | 9,472 | 60 |
| 23 | 34.04 | low | 2-7 | 26,911 | 63 | 2-6 | 13,072 | 68 |
| 28 | 34.04 | low | 2-8 | 57,689 | 68 | 2-7 | 41,179 | 75 |
| 33 | 34.04 | low | 2-9 | 90,917 | 73 | 2-7 | 75,662 | 75 |
| 13 | 42.55 | high | 2-5 | 4,144 | 48 | 2-3 | 411 | 37 |
| 18 | 42.55 | high | 1-6 | 21,990 | 63 | 1-4 | 7,076 | 60 |
| 23 | 42.55 | high | 1-8 | 67,819 | 73 | 1-6 | 45,797 | 75 |
| 28 | 42.55 | high | 1-9 | 121,070 | 77 | 1-7 | 94,418 | 80 |
| 33 | 42.55 | high | 0-9 | 120,886 | 81 | 0-6 | 78,064 | 80 |
| 13 | 34.04 | high | 2-7 | 22,837 | 63 | 2-5 | 16,397 | 60 |
| 18 | 34.04 | high | 1-7 | 51,240 | 68 | 1-6 | 32,532 | 75 |
| 23 | 34.04 | high | 1-9 | 103,842 | 77 | 1-7 | 82,310 | 80 |
| 28 | 34.04 | high | 0-9 | 113,619 | 81 | 0-7 | 74,809 | 84 |
| 33 | 34.04 | high | 0-10 | 165,852 | 84 | 0-7 | 124,407 | 84 |

[a] The unregulated solution was determined by setting $\lambda$ equal to zero, which is equivalent to setting the user cost equal to zero, as occurs in the open access fishery.

[b] The "high" price was produced by solving the price equation using the 1980-81 average of the exogenous variables (sea scallop price, callico scallop landings, and income). The "low" price was produced using the 1981-82 average of these variables.

[c] The optimal season is in weeks where the first week is the first seven days in December. Numbering begins with zero. For example, an optimal season of "5-12" denotes that the season should open at the <u>beginning</u> of the sixth week (delaying the opening five weeks past December 1) and remain open <u>through</u> the thirteenth week.

[d] Negative values resulted because there was a positive net return at the beginning of the week, which was offset by losses in the latter part of the week. Recall that the decision to harvest was made on a weekly basis.

[e] The fishery was not profitable during the second week, but returned to being profitable in the third week owing to growth in value.