

THE COSTS OF INEFFICIENT FISHER REGULATION:

A PARTIAL STUDY OF PACIFIC HALIBUT

by

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It has long been recognized that unrestricted exploitation of fish populations inevitably leads to inefficiency.¹ At best, the absence of controls brings about fishing effort levels that exceed those at which the marginal cost of a fish equals its value to consumers. At worst, this allocative inefficiency is compounded by a technical inefficiency: A given sustained yield is achieved with higher than necessary expenditures of effort. By suitably restricting fishing activity through an appropriate system of catch taxes, a regulatory body could ensure efficient exploitation of a fish population. The regulatory approaches actually used in practice, however, include technological controls (restrictions on the size, power, and other characteristics of boats; port turnaround time; or fishing gear) and limitations on season length or total catch. Each of these regulatory measures is flawed in that it introduces inefficiencies of its own.

The ultimate objective of this paper is to use catch, effort, and stock data from the commercial Pacific halibut fishery to measure the degree of technical inefficiency introduced as a result of that particular fishery's regulatory environment. We begin, however, with a discussion reviewing the rationale for regulation of commercial fisheries and illustrating the sources of inefficiency that can be introduced thereby.

Overexploitation of Fish Stocks and Regulatory Measures

For the purposes of this preliminary discussion it is useful to make several simplifying assumptions. The first of these will also be maintained in the empirical work to follow: The growth rate of a fish population depends only on the population's aggregate biomass, not on the distributions of age or fish size within the population. Second, we will ignore issues relating to limited fishing seasons and assume instead that fishing effort is uniformly distributed

throughout the year. Finally, it is also useful to restrict attention to comparisons of steady state equilibria; that is, situations in which the catch rate equals the natural growth rate leaving the size of the population constant through time.

Let S denote the biomass, or stock, of a fish population, and let $g(S)$ represent the annual rate of growth of the stock net of natural mortality. The graph of $g(\cdot)$ in Figure 1 illustrates the two opposing forces affecting growth rates of unexploited fish populations. On the one hand, the greater the biomass, the more fish there are to breed and grow. On the other hand, the greater the biomass, the greater is the competition for food and possibly other environmental amenities. At low biomasses, the first of these forces dominates. The growth rate increases, albeit at a diminishing rate, with increases in the fish stock. Beyond some critical stock level, however, the second force comes to dominate and the growth rate diminishes with stock.

Each of the ordinates of the function $g(\cdot)$ can be thought of as a sustainable annual yield. For example, if the fish stock were S_1 to begin, and sufficient fishing effort were expended to harvest Q_0 pounds of fish per year, fishing mortality would just offset net natural growth leaving stock unchanged. With equal expenditures of fishing effort in subsequent years, the annual yield of Q_0 pounds could be sustained indefinitely.

It is clear from Figure 1 that any sustainable yield less than the maximum, Q_M , could be achieved with either of two fish stocks. Q_0 pounds per year, for example, could be harvested on a sustainable basis from populations of size S_1 or S_2 . To see how these two alternatives would compare in cost terms, we need add only one additional plausible assumption about fishing technologies: Harvesting any given quantity of fish is less costly the larger is the stock.

Thus Q_0 pounds per year could be harvested on a sustainable basis at an average cost of say c_1 dollars per pound from a population of size S_1 or at a lower average cost of c_2 dollars per pound from a population of size S_2 . The entire sustainable yield/average cost relationship is plotted as the AC curve in Figure 2. It consists of efficient and inefficient branches which indicate per unit costs corresponding to operation in, respectively, the larger and the smaller of the two fish stocks consistent with any given sustainable yield. The MC curve in Figure 2 is marginal to the efficient branch of the AC curve.

Suppose that the demand curve for fish is D_1 in Figure 1. The efficient output rate is Q_1^* while, in the absence of restrictions on exploitation, equilibrium would be reached with output Q_1^e at point E_1 where average cost equals market price. The deadweight welfare loss associated with this allocative inefficiency may or may not be worth correcting through any of a variety of costly regulatory measures.

But it is situations like those associated with demand curve D_2 , not D_1 , that typically lead to regulatory action. Given demand curve D_2 , efficient output is Q_2^* but the absence of regulation would result in equilibrium at point E_2 and output Q_2^e . Unrestricted exploitation leads not only to an inefficient output, but also to actual costs of producing whatever level of output is settled upon that are substantially greater than those which could be achieved.

Any of a variety of controls could be adopted to eliminate or reduce these inefficiencies. At least conceptually, the ideal approach would be a tax equal to the difference between the marginal and the average cost of fish at the output rate where demand and marginal cost schedules intersect.² There appears to be no fishery, however, in which controls take the form of output taxes.³ Rather, under the typical system, regulation involves allowing free access to any

fishing vessel that abides by restrictions on such things as vessel type, crew size, gear employed, length of season, area fished, and port turnaround time. In specifying these restrictions, the most common stated objective of regulatory bodies is to maximize sustained yield from a fish population; that is, to set annual output equal to Q_M in Figure 2.

With demand schedule D_2 , equilibrium at an annual output of Q_M requires fisherman to perceive their average costs to be c_4 dollars per pound. One way to achieve this is with technological controls in the form of vessel type or fishing gear restrictions that increase the resource costs of catching fish by $(c_4 - c_3)$ dollars per pound. The real world equivalent of $c_4 - c_3$ can be enormous. One, perhaps extreme, example is particularly suggestive. Along the Virginia shore of Chesapeake Bay, oysters can be taken only with hand-operated tongs, not with considerably more efficient dredges. In Maryland, dredges may be used, but only when pulled by sailboats except on Mondays and Tuesdays when sailboats may be aided by motorized pusher boats [Alexander, p. 244].

An alternative common strategy for limiting overexploitation involves the use of a non-allocated catch quota; that is, a regulation terminating the fishing season when the fleet's cumulative landings reach a predetermined limit. Such a regulation creates a tendency for fishing effort to be expended at very high rates as each crew scrambles to claim as large a share of the fishery's quota as possible, and can lead to significant curtailments of season lengths. In the Pacific halibut fishery, for example, the use of non-allocated catch quotas led to the reduction of season lengths from the nine months common during the 1920s to less than one month in the 1950s.

Like technological controls, non-allocated catch quotas introduce inefficiencies of their own. First, if capital equipment is specialized to the

particular type of fishing, confining fishing activity to an artificially abbreviated season increases the capital stock needed to support any given annual total effort and reduces the capital stock utilization rate. Second, the short, frantic seasons induced by non-allocated quotas are likely to be characterized by lower catches per unit effort than could be realized with longer, more leisurely seasons. This is due to diminishing returns to fishing effort: For a given fish population, the rate at which fish are caught increases but likely at a decreasing rate with respect to the rate at which effort is expended.⁴

The objective of the empirical work in this paper is the assessment of the waste resulting from the second source of inefficiency identified above, the combination of artificially shortened seasons and diminishing returns to fishing effort. Our application involves the Pacific halibut fishery, one in which a non-allocated catch quota is the primary regulatory instrument and "fishing frenzies" are an institution. The problem of measuring the resulting inefficiency is complicated by the fact that extending the season in any one year will affect not only catch in that year but also the year-ending stock and, therefore, the potential for catching fish in subsequent years. Thus the assessment must take into account the effects of season lengthening over a series of years and must be based on a model incorporating both the technology whereby fishing effort interacts with stock to catch fish and the growth law that describes the natural evolution of stock levels over time. The next section establishes the theoretical relationships among catch, effort, stock, and season length that form the building blocks of such a model. From them, with biological and institutional features of the halibut fishery as a guide, a statistical model is assembled. Finally, the statistical model is estimated and the results used

as a basis for judging the magnitude of this one particular variety of inefficiency in regulated commercial fisheries.

Theoretical Relations Among Stock, Catch, Effort, and Season Length

Let $S(\tau)$ denote the weight of the "adult biomass" of a fish population at time τ , where τ is a continuous variable. By the "adult biomass," we mean the portion of the population that is vulnerable to the fishery; that is, the portion above a statutory size minimum or sufficiently large to bite hooks or become entangled in nets. Even if there were no fishing, the adult biomass would vary over time as the result of two distinct phenomena: growth and natural mortality of existing adults, and additions of new adults due to the recruitment of adolescents.

The first of these phenomena is modelled as a continuous process. Let the instantaneous rate of growth of adults net of natural mortality, $\dot{S}(\tau)$, be given by

$$\dot{S}(\tau) = \frac{dS}{d\tau} = G S(\tau)(M - S(\tau)) \quad (1)$$

where $G > 0$ and $M > 0$ are parameters characterizing the population growth law.⁵ This function possesses the qualitative features of $g(\cdot)$ graphed in Figure 1 although now ordinates of the function are interpreted as instantaneous growth rates of the adult biomass.

Recruitment, the second phenomenon affecting the size of an unexploited population, is modelled as a discrete process. In other words, we assume that all maturing adolescents in a given year enter the adult biomass at the same moment. For integer values of t , define R_t as the biomass of adolescents maturing during year t . It is natural to expect that R_t will be related to the

size of the cohort's parent stock and a widely adopted functional form for this relationship is

$$R_t = \frac{a_1 S_{t-n}}{1 + a_2 S_{t-n}} \quad (2a)$$

where $a_1 > 0$ and $a_2 > 0$ are parameters, n is the (integer) number of years required for fish to mature, and S_t is an "average" stock for year t . S_{t-n} , therefore, is the biomass of the parent stock of year t recruits.⁶

The popularity of this form is due to the fact that appropriate parameter values generate functions, like the one graphed in Figure 3, for which recruitment is nearly constant over broad ranges of values for S_{t-n} . This is a common feature of fish populations. Since each female lays thousands of eggs and only a tiny proportion of them develop into adult fish, recruitment primarily depends, not on the size of the parent generation, but on the ability of the ecosystem to support life in the embryonic, larval, and juvenile stages. Indeed it may well be appropriate to drop S_{t-n} as an argument altogether and replace (2a) with

$$R_t = h(Z_t; \gamma) \quad (2b)$$

where Z_t is a vector reflecting environmental conditions in years t , $t-1$, $t-2$, . . . , and $t-n$, and γ is a vector of parameters.

Now imagine that fishing effort is devoted to catching a portion of the adult biomass. Let $\dot{C}(\tau)$ denote the instantaneous rate at which fish are caught at time τ and assume

$$\dot{C}(\tau) = q S(\tau) (E(\tau))^b \quad (3)$$

where $E(\tau)$ is the rate at which fishing effort is expended at time τ (measured, for example, in units of "boat-days per day" or, simply, "boats") and $q > 0$ and

$0 < b \leq 1$ are parameters. This particular form of the "fishing production function" incorporates the following plausible features. For a constant effort rate, the catch rate increases with the stock. For a constant stock, the catch rate increases with effort, possibly at a diminishing rate.⁷

The fishery's annual fishing seasons alternate with off-season periods. For simplicity, we imagine the fishery's activities as occurring over a sequence of "years," each incorporating a consecutive season and off-season and beginning on a season opening day.⁸ We assume that a given year's recruits enter the adult biomass as a discrete injection occurring at the beginning of the year. The evolution of the stock over the balance of the year is determined by equations (1) and (3). Given fishing effort rate $E(\tau)$, the population's rate of growth net of natural and fishing mortality is given by

$$\dot{S}(\tau) = G S(\tau)(M - S(\tau)) - q S(\tau)(E(\tau))^b \quad (4)$$

Limit attention to a time interval, say $[\tau_1, \tau_1 + \Delta\tau]$, on which $E(\tau) = E$, a constant, and define constants $f = q E^b$ and $H = G M - f$. Then (4) can be rewritten as

$$\dot{S}(\tau) = S(\tau)(H - G S(\tau))$$

or

$$[S(\tau)(H - G S(\tau))]^{-1} \dot{S}(\tau) = 1 \quad (5)$$

Integrating both sides of (5) with respect to τ , from τ_1 to $\tau_1 + \Delta\tau$, and solving for $S(\tau_1 + \Delta\tau)$ yields⁹

$$S(\tau_1 + \Delta\tau) = \frac{H S(\tau_1)}{G S(\tau_1)(1 - \exp(-H \Delta\tau)) + H \exp(-H \Delta\tau)} \quad (6)$$

Equation (6) can be used to relate stock at the end of a season, or off-season, to stock at the beginning. Let S_{1t} and S_{2t} denote the adult biomasses

at the beginning and end, respectively, of the season in year t . The interpretations of these and subsequently defined variables are illustrated in Figure 4's sketch of a representative stock profile. Let T_{1t} denote the length of year t 's season and let E_t denote the (constant) rate at which fishing effort is expended during the season. Then if (6) is evaluated

with τ_1 and $\tau_1 + \Delta\tau$ interpreted as the beginning and ending season dates, the result is

$$S_{2t} = \frac{H_t S_{1t}}{G S_{1t} (1 - \exp(-H_t T_{1t})) + H_t \exp(-H_t T_{1t})} \quad (7)$$

where $H_t = G M - q E_t^b$. Now let S_{3t} denote stock at the end of the off-season in year t and let T_{2t} denote the off-season's length. Then with $(\tau_1, \tau_1 + \Delta\tau)$ interpreted as the off-season (an interval in which $E = 0$ and $H = G M$), (6) yields

$$S_{3t} = \frac{G M S_{2t}}{G S_{2t} (1 - \exp(-G M T_{2t})) + G M \exp(-G M T_{2t})} \quad (8)$$

Equations (7) and (8) describe the evolution of stock from the beginning of a fishing season to the end of the subsequent off-season. To complete the description for a full annual cycle, recruitment is added to the off-season ending stock:

$$S_{1t+1} = S_{3t} + R_{t+1} \quad (9)$$

Finally, total catch in year t , C_t , can be obtained by integrating the catch rate over the season:

$$C_t = \int_0^{T_{1t}} f_t S(\tau_1 + \Delta\tau) d\Delta\tau$$

where $f_t = q E_t^b$ and, again, r_1 is interpreted as the opening date of the season in year t . Substituting for $S(r_1 + \Delta r)$ from equation (6) with $H = H_t$ and integrating yields¹⁰

$$C_t = (f_t/G) \ln(1 + \frac{G}{H_t} S_{1t} (\exp(H_t T_{1t}) - 1)) \quad (10)$$

Solving for T_{1t} yields

$$T_{1t} = (1/H_t) \ln(1 + \frac{H_t}{G} S_{1t} (\exp(\frac{G C_t}{f_t}) - 1)) \quad (11)$$

A Statistical Model for Pacific Halibut

Imagine that one had a set of provisional values for the parameters embedded in equations (7) through (11). Then, if given information on fishing effort, season and off-season lengths, the variables influencing annual recruitment, and an initial stock level, equations (7), (8), and (9) could be used to project a series of season opening stock levels. Given these estimates of season opening stocks and, again, information on fishing efforts and season lengths (catches), equation (10) (equation (11)) could be used to project the corresponding annual catches (season lengths). Intuitively it is clear, then, that equations (7) through (11) provide a basis for estimating the system's unknown parameters: Choose estimates for which projected stocks and catches (season lengths) "match" actual figures as closely as possible.

Specifying the details of this estimation strategy requires more careful consideration of the institutional aspects of the Pacific halibut fishery. The fishery is divided into geographically delineated statistical areas. A given year's catch in a given area is determined, albeit subject to error, by a non-allocated catch quota imposed before the season opens.¹¹ The stock of boats

available at the beginning of the season determines a maximum rate at which fishing effort can be expended.¹² Effort is perfectly inelastically supplied at this maximum rate throughout the season.¹³ The length of the season in a given area is determined as the time required for the fleet to land the area's quota. It seems appropriate, therefore, to treat the current season's catch and effort rate, along with lagged values of these and other variables, as predetermined, and to view current stock and season length as jointly determined endogenous variables.

The available estimates of adult biomasses for each statistical area of the Pacific halibut fishery are best interpreted, not as beginning or ending season stocks, but as stock levels at season midpoints.¹⁴ The midseason biomass in year t , S_t , can be related to both the beginning and ending season stocks using equation (6):

$$S_t = \frac{H_t S_{1t}}{G S_{1t}(1 - \exp(-H_t T_{1t}/2)) + H_t \exp(-H_t T_{1t}/2)} \quad (12)$$

and

$$S_{2t} = \frac{H_t S_t}{G S_t(1 - \exp(-H_t T_{1t}/2)) + H_t \exp(-H_t T_{1t}/2)} \quad (13)$$

Initial estimation experiments using the recruitment function (2a) were unsuccessful: The quality of fit continued to improve as a_1 and a_2 increased without bound in fixed proportion. This implies that R_t , in fact, is independent of S_{t-n} and suggests abandoning (2a) for (2b). Perhaps the single most important "environmental" determinant of recruitment is the rate of mortality due to the incidental catch of halibut by other fisheries.¹⁵ Since incidentally caught halibut tend to be below legal size, their deaths affect recruitment in subsequent years rather than the size of the current adult population. Accurate

figures for by-catch mortality are unavailable but it is widely believed that its effects were minor before 1960 and progressively more significant thereafter. Thus we model recruitment as being constant through 1959 and changing (presumably decreasing) in a linear trend from 1960 onward:

$$R_t = A_1 \quad \text{for } t \leq t_0 \quad (2b')$$

$$A_1 + \frac{t-t_0}{t_{\max} - t_0} (A_2 - A_1) \quad \text{for } t > t_0$$

where t_0 corresponds to 1959, t_{\max} to the last year of the sample, and $A_2 = R_{t_{\max}}$.

Starting with equations (11) and (12), use equation (9) with R_t given by equation (2b') to substitute for S_{1t} in terms of S_{3t-1} , equation (8) to substitute for S_{3t-1} in terms of S_{2t-1} , and equation (13) to substitute for S_{2t-1} in terms of S_{t-1} . The result is a pair of simultaneous equations determining period t values for endogenous variables T_1 and S in terms of predetermined observable variables. In symbolic terms

$$T_{1t} = \phi_1(\beta'; X_t) \quad (14)$$

$$S_t = \phi_2(\beta'; T_{1t}, X_t) \quad (15)$$

where $\beta' = (G, M, q, b, A_1, A_2)$ is the vector of parameters of the population growth relationship, the fishing production function, and the recruitment function; and $X_t = (E_t, C_t, t, T_{1t-1}, T_{2t-1}, E_{t-1}, S_{t-1})$ is a vector of variables predetermined as of the beginning of year t .

Data, Estimation, and Simulation Results

Annual catch, effort, and season length data for each of the fishery's statistical areas have been recorded since the late 1920s when the International Pacific Halibut Commission (IPHC) was formed.¹⁶ IPHC estimates of adult

biomasses are less complete. Consequently, this application will be limited to Statistical Area 2 and to a time period beginning in 1935. We end the sample at 1972 since, in 1973, the IPHC increased the legal minimum size of halibut and so effectively redefined this study's concept of the adult stock.¹⁷ Statistical Area 2 consists of the waters off a 1250 mile stretch of North American Pacific coastline from northern California to Cape Spencer, Alaska. In 1972, the last year of the sample, Area 2 accounted for 38% of the fishery's catch. Definitions and dimensions for the model's variables and the actual time series used in estimation are given in the Appendix.

Rearranging (14) and (15) and augmenting them with additive disturbance terms yields

$$T_{1t} - \phi_1(\beta'; X_t) = e_{1t} \quad (16)$$

$$S_t - \phi_2(\beta'; T_{1t}, X_t) = e_{2t} \quad (17)$$

We assume that

$$e_{1t} = \rho_1 e_{1t-1} + u_{1t}$$

$$e_{2t} = \rho_2 e_{2t-1} + u_{2t}$$

where u_{1t} and u_{2t} are serially uncorrelated and jointly normally distributed.

Quasi-first-differencing of (16) and (17) yields

$$\Phi_1(\beta; T_{1t}, X_t, X_{t-1}) = u_{1t} \quad (18)$$

$$\Phi_2(\beta; S_t, T_{1t}, X_t, X_{t-1}) = u_{2t} \quad (19)$$

where $\beta = (\beta', \rho_1, \rho_2)$ and

$$\Phi_1(\beta; T_{1t}, X_t, X_{t-1}) = T_{1t} - \phi_1(\beta'; X_t) - \rho_1(T_{1t-1} - \phi_1(\beta'; X_{t-1}))$$

and

$$\Phi_2(\beta; S_t, T_{1t}, X_t, X_{t-1}) = S_t - \phi_2(\beta'; T_{1t}, X_t) - \rho_2(S_{t-1} - \phi_2(\beta'; T_{1t-1}, X_{t-1}))$$

The parameter vector in equations (18) and (19) was estimated by full information maximum likelihood (FIML) for the time period 1937 - 1972.¹⁸ Results are reported in Table 1. The R^2 s are squared simple correlation coefficients between the series of optimal one-step-ahead forecasts of season length and stock, and the corresponding actual series. The parameter estimates are valued primarily for their use in the dynamic simulation experiments; few of them are interpretable on an individual basis. Point estimates of A_1 and A_2 do suggest that, as expected, recruitment decreased after 1960, although this finding is not statistically significant. One result foreshadows the implications of the simulation exercises: The estimate of b is only slightly less than one and is not significantly different from one at conventional levels.

Our main objective in estimating the model was to obtain parameter values that can be used as a basis for simulation experiments. A program of lengthening the seasons over which fishing efforts are expended has the potential for increasing the catch per unit effort over the long run. To measure this effect, simulations of catches and stocks were undertaken for the actual series of total efforts and for actual and hypothetical series of season and off-season lengths.

Prior to 1924, the halibut fishery operated year around. Fishing conditions were hazardous during the winter, however, and winter-caught halibut tended to be of low quality. These considerations led to treaty negotiations which resulted in closure of the fishery for three months a year beginning in 1924. Accepting this sort of closure as consistent with efficient exploitation of the halibut population, the hypothetical season length was set equal to $0.75 \times 365.25 = 273.9375$ days.

With our estimate of midseason biomass in 1937, we used equation (12) to estimate the opening season biomass in 1937. Equation (10) was then used to simulate catch in both the actual and hypothetical 1937 seasons. Equations (7), (8), and (9) were used next to simulate the opening season stock for 1938 for each of the cases. By iterating this process, entire series of simulated catches for 1937 - 1972 for both actual and hypothetical season lengths were generated.

Actual fishing seasons were relatively short (less than 100 days) for each of the 20 years from 1941 through 1960. Had actual total efforts been applied uniformly over 9 month seasons during this interval, effort rates would have been lower than actual ones by an average of 82%. Yet even for this period, the simulated catches for the hypothetical seasons averaged only 2.2% higher than those for the actual seasons.¹⁹ The potential gains from applying fishing effort at more leisurely rates appear to be small.

Notice that the sample period used for estimation provides a reasonable basis for making the projection described in the previous paragraphs. The hypothetical effort rates during the 1941 - 1960 seasons range from 820 to 1,410 skate-soaks per day (See the data appendix). Thus the projection is for effort rates that are more-or-less within the sample since the range of actual rates for the estimation period is from a low of 1,140 to a high of 9,810 skate-soaks per day. Over this range, no significant tendency toward diminishing returns to effort was detected. Again, the estimate of b was not significantly less than 1. It is possible, of course, that the onset of diminishing returns does not occur until even higher effort rates. With this in mind, it is interesting to note that Area 2 fishing effort rates in recent years (1984 and 1985, for example) were in the neighborhood of 20,000 skate-soaks per day. At these levels, the benefits of season lengthening may yet be important.

Data Appendix

The gear used in catching halibut are called "skates," long lines with baited hooks attached at intervals. The method involves deploying a skate, leaving it in the sea for several hours, then retrieving it. This activity, undertaken for a single skate, is called a "skate-soak," the basic unit for measuring physical effort input in commercial halibut fishing.

The following data are for Statistical Area 2. Catch, effort, and season length data were obtained from various Annual Reports of the IPHC. Stock estimates are from Deriso and Quinn (1983).

C: (catch) 1,000,000 lbs.
 T_1 : (season length) days
 T_2 : (interval between this season and the following season) days
S: (adult biomass) 1,000,000 lbs.
 E^* : (total effort) 1,000 skate-soaks
E: (effort rate = E^*/T_1) 1,000 skate-soaks per day

YEAR	C	E^*	T_1	T_2	S
1935	23.559	379.6	159	191	116.8
1936	23.319	424.8	148	217	118.4
1937	24.073	389.5	135	246	120.6
1938	24.109	341.0	120	245	121.6
1939	25.590	412.0	120	246	121.1
1940	26.403	425.9	104	261	118.4
1941	24.290	386.6	91	289	114.7
1942	23.434	356.1	75	290	113.2
1943	25.361	349.2	66	334	116.0
1944	26.349	301.6	51	295	129.5
1945	23.796	296.4	46	319	151.7
1946	29.168	346.2	42	323	168.9
1947	27.739	319.5	39	327	177.7
1948	27.827	311.9	32	333	183.8
1949	26.412	308.8	34	331	189.9
1950	26.997	306.3	32	333	196.9
1951	30.598	347.1	36	343	203.0
1952	30.808	320.6	34	334	205.3
1953	32.711	252.4	32	332	204.4
1954	36.791	264.8	27	334	199.3
1955	27.806	225.6	31	343	187.3
1956	35.097	263.9	45	301	173.5
1957	30.534	300.5	54	314	165.8
1958	30.210	294.5	66	296	165.3
1959	30.530	307.2	75	291	167.8
1960	31.758	300.5	98	276	169.8

(continued)

YEAR	C	E*	T ₁	T ₂	S
1961	28.860	298.8	120	244	169.7
1962	28.718	337.1	122	243	166.3
1963	26.170	334.9	205	153	157.9
1964	19.569	258.2	137	228	146.9
1965	24.252	278.7	137	236	138.2
1966	23.259	279.7	108	257	133.0
1967	19.719	240.3	159	202	128.4
1968	16.394	187.5	164	204	122.9
1969	22.377	272.5	137	216	117.2
1970	19.885	266.8	149	228	112.6
1971	16.773	218.6	178	182	110.8
1972	16.283	232.5	101	273	110.7

Notes

¹Gordon (1954) appears to have provided the seminal piece in what is now a sizable literature on the economics of commercial fisheries. Since our paper is concerned with a rather specific aspect that is somewhat out of the main stream of discussion, it would not benefit significantly from the context provided by a comprehensive literature review. Such a review is given by Schellberg (1988).

²If, as assumed here, the growth rate of a fish population depends only on its biomass, the appropriate tax per pound would be independent of the size of fish caught. If the population's growth rate depends on its age distribution as well as its biomass, the appropriate tax per pound would vary inversely with age of fish.

³The Fisheries Conservation and Management Act of 1976 empowers the National Marine Fisheries Service to impose fees on foreign fishing vessels wishing to fish in the "US Fishery Conservation Zone." The fees established for 1977 included a charge equal to 3.5 percent of the estimated dockside value in 1975 of species which foreign vessels were allowed to catch. The announced criteria leading to imposition of these fees included, however, "1. Fees will not be used as a management tool to restrict foreign fishing. Foreign fishing effort will be controlled by management plans [i.e. quotas]." [Federal Register, 42, p. 8176]

⁴Suppose, for example, that different areas of the fishing grounds were characterized by different productivities. Then with say 10 boats fishing on each of 100 days, each vessel could operate in the most productive areas every day. On the other hand, with 100 boats fishing on each of 10 days, congestion might force some boats to operate in marginally less productive areas each day. 1000 boat-days of total effort would catch more fish in the first case than in the second.

⁵This is the form of the growth function used in the Schaefer (1958) model of the dynamics of exploited fish populations. Schnute (1977) discusses estimation of the Schaefer production model using catch and effort data. Schnute's procedures do not make use of stock estimates nor do they address the simultaneous determination of catch and season length.

⁶This is the Beverton-Holt recruitment function. For a discussion, see Clark (1976). Equation (2a) embodies the implicit assumption that the "adult population," defined as the set of fish vulnerable to the fishery, is precisely the same as the set of sexually mature fish. This seems to be approximately true for Pacific halibut. The set of "adults," by either definition, consists of fish aged eight years or older.

⁷With $b = 1$, equation (3) describes what is commonly termed a "mass-contact-rate" technology reflecting the seeming similarity between fishing and chemical processes in which two different types of molecules react at rates proportional to the product of their concentrations. It would be appealing to

allow the possibility of diminishing returns to stock as well. Replacing (3) with

$$\dot{C}(\tau) = q(S(\tau))^a(E(\tau))^b \quad (3')$$

for $0 < a \leq 1$ would accomplish this. The problem with this specification is a practical one: Integrals of the corresponding version of equation (5) would have no closed form expression.

⁸Thus these "years" needn't start on January 1 nor be 365 days in length.

⁹Equation (6) is correct for $H \neq 0$. If $H = 0$ the definite integral of (5) equals the limit, as H approaches 0, of the expression on the right-hand-side of (6). Thus equation (6) covers both cases when appropriately interpreted.

¹⁰For the $H = 0$ case, the right-hand-side of (10) is replaced by its limit as H approaches 0.

¹¹Regulators monitor landings and try to anticipate the day on which the quota will be reached. This anticipated date is fixed as the season closing date two or three days in advance. As a result, actual catches differ from predetermined quotas, normally by small amounts. In addition to the quota, a maximum season length is announced at the start of the season. In the statistical area examined in our empirical work, the quota was the binding constraint in 31 of the 36 years in the sample.

¹²For a time, the maximum fishing effort rate was also influenced by port turnaround time limitations that resulted from a voluntary agreement among boat operators aimed at lengthening the seasons. This agreement broke down with increased entry during the 1970s by boats not "licensed" by the International Pacific Halibut Commission.

¹³This assumption, while probably valid when applied to the fishery as a whole, would be a bit suspect if applied to a small segment of the fishing grounds since crews are free to direct their effort to the areas deemed most productive. As explained in the next section, the statistical area analyzed here extends along a huge stretch of coastline and is fished by boats from many home ports. Consequently, it is infeasible for most crews to reallocate their effort across statistical areas, at least in the short-run.

¹⁴It is worth emphasizing that stock estimates are merely that: "estimates" based on catch statistics, not "measurements" in any meaningful sense. If the model used by fishery biologists to obtain these estimates were the same as the one used here, our results would be preordained: We would simply recover the parameter values reflected in the biologists' estimates. In fact, the stock estimates are based on an "age-structured" model that recognizes different growth and natural and fishing mortality rates for different age cohorts. See Deriso and Quinn (1983).

¹⁵Foreign trawler operations are the primary cause of by-catch mortality. Incidentally caught halibut are supposed to be thrown back. Many are not. Some are, but subsequently die of injuries.

¹⁶Various Annual, Scientific, and Technical Reports of the IPHC are the primary data sources for this study.

¹⁷There is another impediment to extending the sample much beyond 1972. In 1979, the IPHC modified its regulation of Area 2 by introducing separate quotas (and, therefore, separate season lengths) for subareas 2A, 2B, and 2C.

¹⁸Since the model is recursive, the kernel of the concentrated log-likelihood function is simply

$$L = (-N/2)\log \det \Gamma$$

where Γ is the 2 x 2 matrix with ij element $N^{-1}\sum_{t=1}^N \phi_{it}\phi_{jt}$, and N is the number of observations. See Amemiya (1977). Asymptotic standard errors were estimated using a numerical second derivative estimate of the Hessian of L . The first two years in the sample could not be used for estimation due to the requirement of lagged values.

¹⁹Techniques like those developed in Bianchi et. al. (1981) could be used to place confidence bounds on this estimate of the effects of season lengthening. It seems likely, though, that conventionally sized confidence intervals would contain zero.

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Table 1

FIML Estimates of Equations (18) and (19)

Parameter	Estimate	Asymptotic Standard Error
q	5.893E-04	5.803E-05
b	0.9585	0.0498
G	4.078E-06	2.491E-06
M	188.52	48.00
A ₁	22.674	14.324
A ₂	12.695	15.389
ρ_1	0.6233	0.1357
ρ_2	0.9042	0.1174

Number of observations = 36

Log of likelihood function = -193.874

R²* for

Season Length	0.972
Stock	0.984

* Squared simple correlation coefficients for actual and one-step-ahead forecast series of season length and stock.

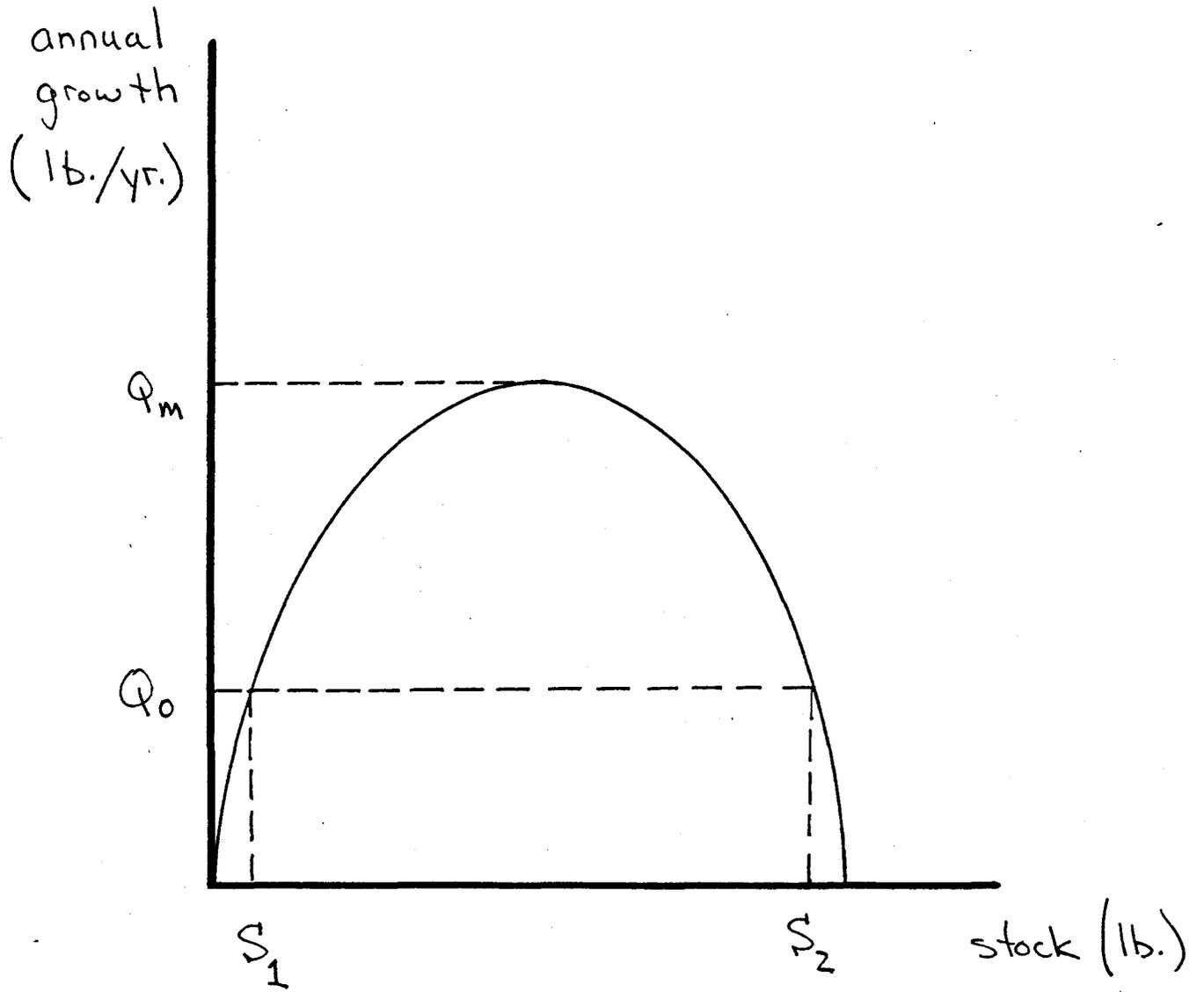


Figure 1

(\$/lb.)

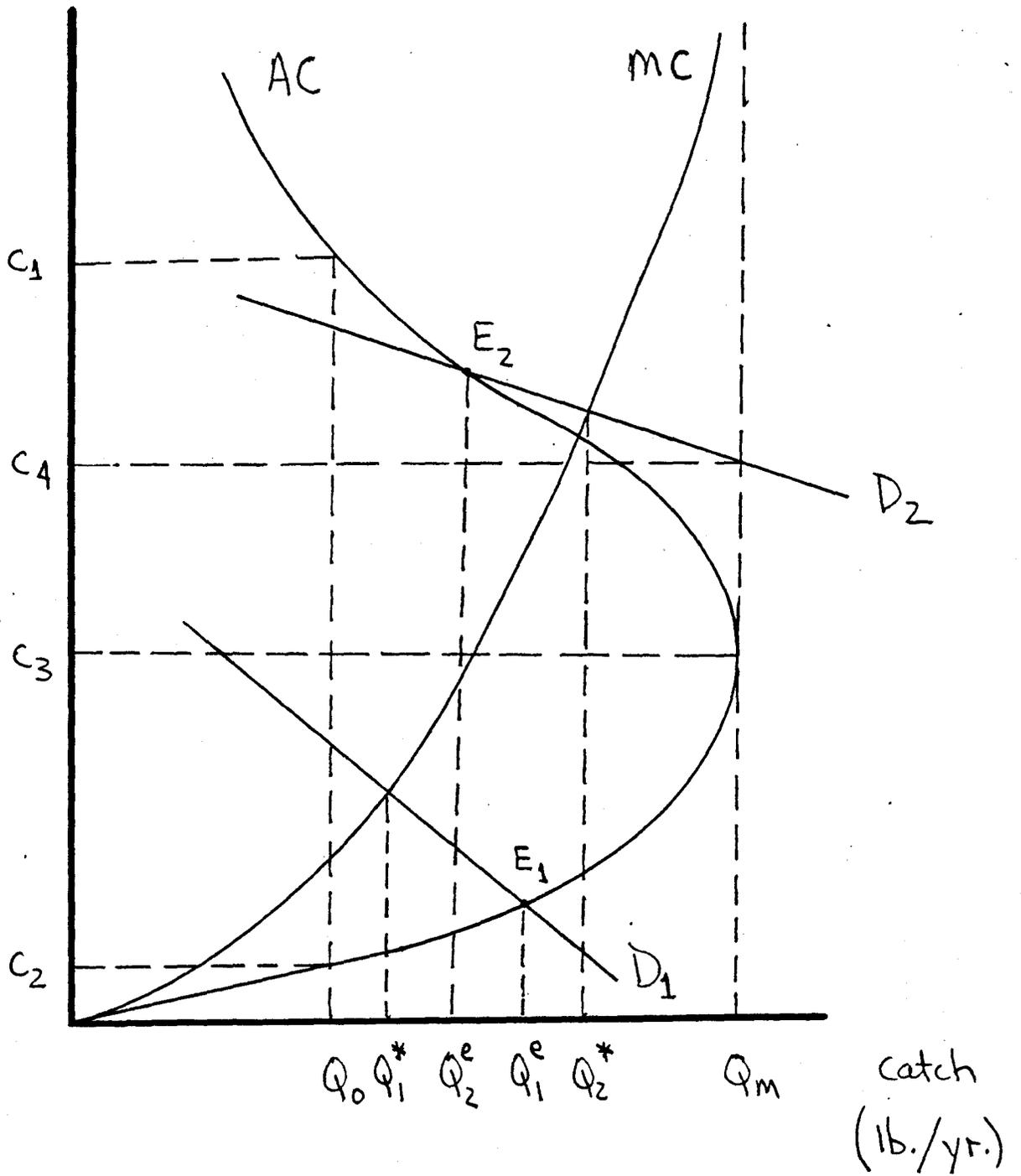


Figure 2

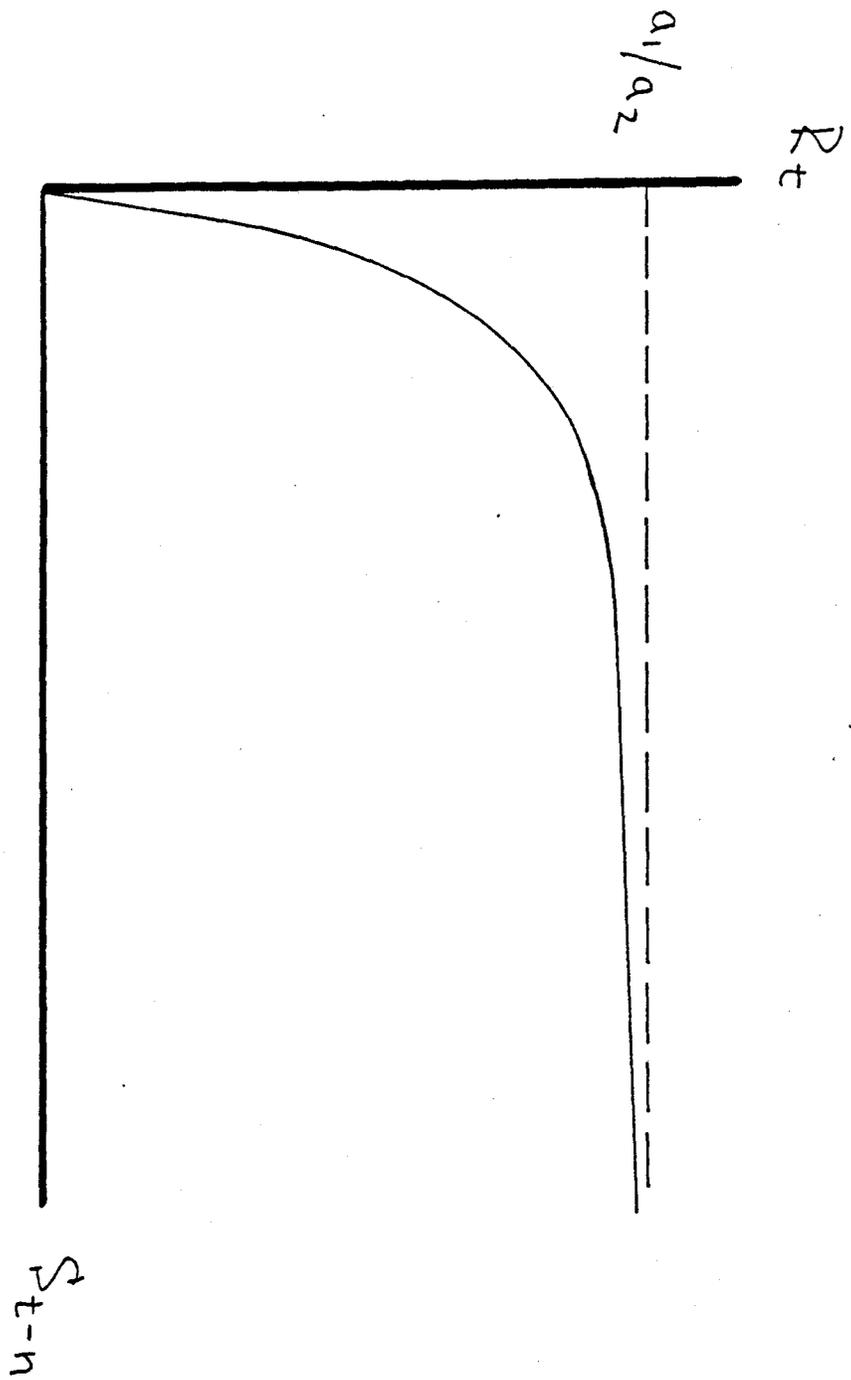


Figure 3.

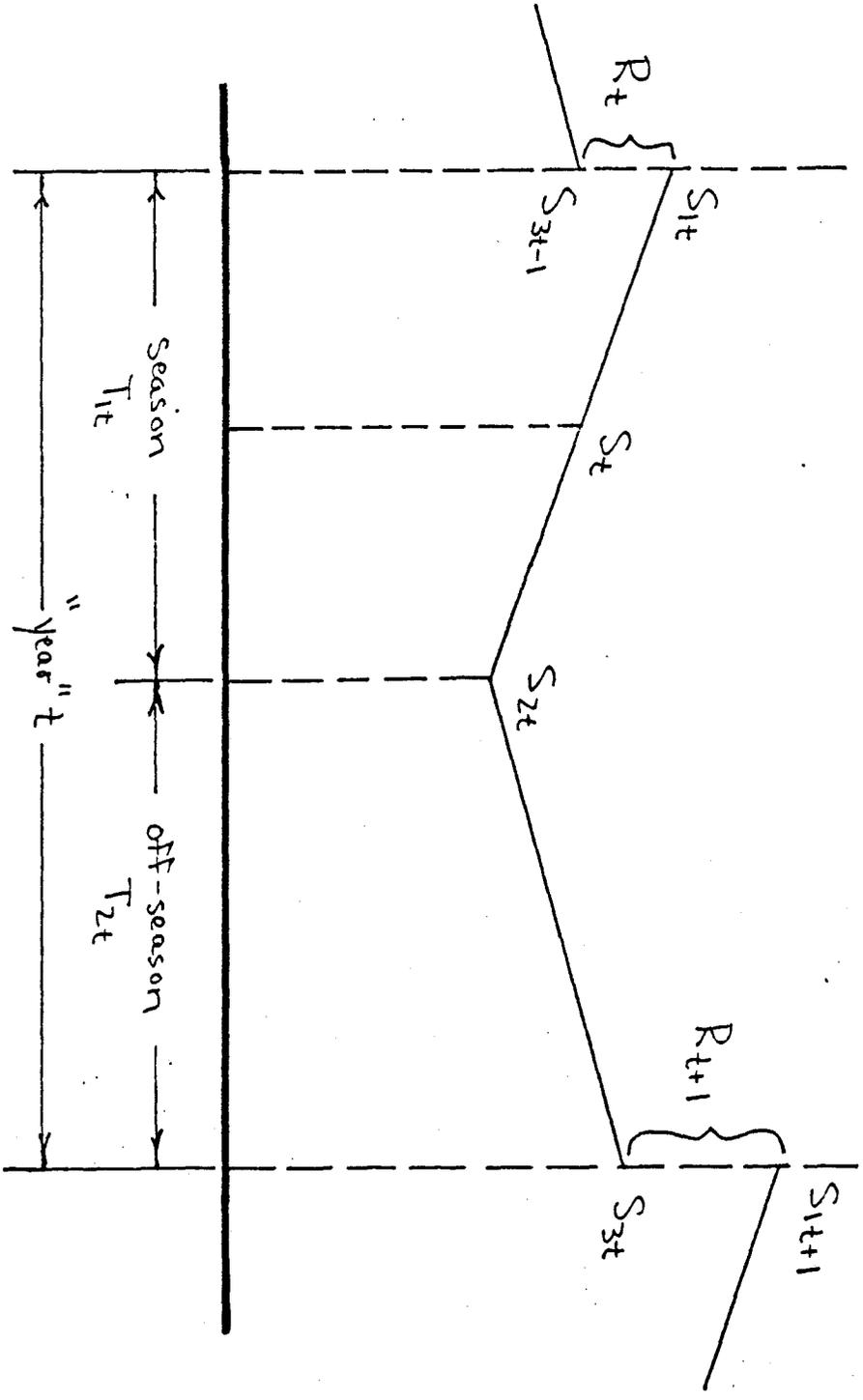


Figure 4.