Optimal Fisheries Investment: Comparative Dynamics for a Deterministic Seasonal Fishery

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A dynamic fisheries model is developed to simultaneously optimize investment in the resource stock (the fish) and investment in the capital stock (the fleet). Each of these investment problems faces a major complication; investment in the resource is constrained by the natural population dynamics, while investment in the physical capital stock tends to be irreversible because capital used in natural resource industries is often nonmalleable. The model assumes a seasonal fishery in which annual escapement and capital investment levels can be controlled. A dynamic programming approach is used to analyze the model heuristically and numerically. The comparative dynamics of optimal investment strategies are studied, with regard to (i) delays in investment, (ii) population dynamics parameters, (iii) fish price, (iv) capital cost, (v) depreciation rate, and (vi) discount rate. In particular, the depreciation rate and the ratio of unit capital costs to unit operating costs play interesting and complex roles in determining optimal investment levels.

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Un modèle de pêche dynamique a été élaboré dans le but d'optimiser l'investissement dans la ressource (le poisson) en même temps que l'investissement en capital (la flottille). Chacun de ces investissements rencontre une complication majeure : l'investissement dans la ressource doit subir la contrainte de la dynamique de population naturelle, alors que l'investissement en capital physique tend à être irréversible parce que, souvent, le capital utilisé dans les industries de ressources naturelles est non malléable. Le modèle suppose une pêche saisonnière dans laquelle peuvent être réglés les niveaux d'échappement annuel et de mise de fonds. On utilise une programmation dynamique pour analyser le modèle de manière heuristique et numérique. La dynamique comparative des stratégies d'investissement optimales est étudiée sous les aspects suivants : (i) retards dans l'investissement, (ii) paramètres de dynamique de population, (iii) prix du poisson, (iv) coût en capital, (v) taux d'amortissement et (vi) taux d'escompte. Le taux d'amortissement, en particulier, ainsi que le rapport du coût en capital unitaire au coût d'opération unitaire jouent des rôles intéressants et complexes dans la détermination des niveaux d'investissement optima.

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THE chronic problem of overcapacity in fisheries has been well documented, but analytical studies of optimal fleet sizes and fisheries investment strategies have been rare. On the other hand, determination of optimal investment levels and optimal capital stocks is a popular topic in the economics literature, but with few exceptions little effort has been made to apply this theory to renewable resource management.

The difficulties in utilizing economic theory to deal with fisheries investment problems are twofold. First, fisheries tend to be faced with the problem of nonmalleability of capital; specialized fishing boats, like forestry and mining machinery, often have few if any alternative uses. Hence, investment is irreversible — capital cannot be removed from the fishery except through natural depreciation. This problem of irreversibility was discussed in general terms by Arrow (1968) and in the context of exhaustible resource production by Campbell (1980) and Lasserre (1983). Second, in fisheries management the question of investment in the capital stock (the fleet) cannot be separated from "investment" in the resource stock (the fish), the latter being accomplished by

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controlling harvest rates or escapements. The resulting joint investment problem is faced each season; decisions regarding desired fleet size and desired fish stock size must be made simultaneously.

Due to these complexities, most fisheries management models to date have concentrated on the resource stock, treating the capital stock as given. Those that have considered capital investment explicitly have generally used simplifying assumptions to avoid either the irreversibility problem or the dynamic joint investment problem described above. An example of the former is that of Smith (1968), in which both the fish population and the fleet size vary over time, but capital is treated as malleable (an assumption that could be reasonable for fisheries that have access to the capital stock of a larger "neighboring" fishery). The latter problem of dynamic joint investment is avoided if investment can be assumed to be a once-and-for-all irreversible decision at the outset (Clark and Kirkwood 1979; Dudley and Waugh 1980; Silvert 1977); this would be the case, for example, if future fish populations are independent of current stock levels. Naturally, neither of the above simplifications applies in general. A more complete analysis has been undertaken by Clark et al. (1979), who solved a continuous-time deterministic version of the irreversible investment problem, with two state variables (biomass and fleet capacity) and two decision variables (fishing effort and investment) varying over time. Recently, McKelvey (1983) studied a similar model, involving the optimal mix of "specialist" and "generalist" vessels in a fishing fleet.

This paper extends the study of optimal capital investment in renewable resource industries by expanding the work of Clark et al. (1979). The model here is similar to theirs but more realistic in a number of respects: (i) a year-by-year time frame is used, with fishing taking place continuously within each season, (ii) the decision variables are end-of-season escapement and yearly investment (as opposed to instantaneous fishing effort and investment in the CCM continuous-time case), and (iii) delays are allowed between the time at which investment decisions are made and the time at which these investments come online.

In addition, a dynamic programming approach is used to study arbitrary stock-recruitment functions, including the Beverton–Holt and Ricker forms, and to obtain detailed comparative dynamics results. Specifically, this paper describes the effects on optimal investment/escapement policies of the following factors: (i) discrete-time versus continuous-time analysis, (ii) investment delays, (iii) productivity and carrying capacity of the resource stock, (iv) fish price, (v) capital cost, (vi) discount rate, and (vii) depreciation rate. In a companion paper (Charles 1983), a stochastic version of the model is used to study the role of uncertainty in fisheries investment problems.

The Model

An aggregated (single-species single-cohort) fish stock is assumed, with the biomass at the beginning of season $n + 1$, R_{n+1}, depending on the end-of-season escapement from the previous season, S_n, according to the stock-recruitment relationship $R_{n+1} = F(S_n)$. In applications discussed here, this reproduction function will be either pure compensatory ($F' > 0, F'' < 0$) or overcompensatory, using the Beverton–Holt or Ricker form, respectively (Beverton and Holt 1957; Ricker 1954). Natural mortality is constrained to occur at the end of the fishing season, but fishing mortality occurs continuously during the season, with biomass following the common differential equation $dx/dt = -h(t) = -qE(t)x(t)$, where $h(t)$ is the harvest rate, $E(t)$ is the instantaneous aggregated fishing effort, q is a constant catchability coefficient, and initially $x(0) = R_n$ in year n. The escapement is then $S_n = R_n \exp\left[-q\int_0^T E(t)dt\right]$ where T is a fixed maximum season length.

The capital stock, or fleet capacity, K, is represented here by the maximum instantaneous fishing effort; at any point t in the season n, effort is constrained by $0 \leq E(t) \leq K_n$. Hence, K_n depicts the catching power of the fleet, an aggregated measure including fishing vessels, together with nets, machinery, engines, and training of the fishermen.

For simplicity, the cost per unit of new fleet capacity is assumed to be a constant, δ, irrespective of the current level of capacity. Furthermore, it is assumed that this cost must be paid in full at the time the new capacity is ordered. The unit capital cost may be considered to include a fraction of processing capacity costs, where appropriate. (In practice, the type of vessel, or the mix of vessel types, chosen for a fishery may affect the unit operating cost and the unit capital cost in different ways. This complication is not included here; the fleet is taken to be homogeneous.)

Depreciation is assumed to occur at the end of each season, with a constant fraction γ (the depreciation rate) of the current capital stock wearing out or otherwise being removed from the fishery at that time.

Perhaps the most important assumption in this model, as in the Clark et al. (1979) model, is the irreversibility of investment. It is assumed here that the fleet capacity cannot be decreased at will but only through the process of depreciation. Hence, the dynamics of the capital stock, K, can be expressed as follows:

$$K_{n+1} = (1 - \gamma)K_n + I_{n+1}; \quad I_{n+1} \geq 0$$

where the investment I_{n+1} becomes available in year $n + 1$. (This key irreversibility assumption could be relaxed somewhat given either a positive scrap value for fishing capital (see Clark et al. 1979, p. 35–37) or the possibility of bringing outside vessels, either domestic or foreign, into the fishery on a temporary basis (see, e.g., McKelvey 1981). In any case, investment is not entirely irreversible in the model, since capital depreciates annually, as is the situation in real-world fisheries.)

A further consideration in dealing with investment policies is the possibility of a delay existing between the time an investment decision is made and the time the corresponding new capacity becomes available. Such delays may arise due to the time necessary to construct new vessels and/or transport them to the fishing grounds. In a deterministic world, such investment delays increase the effective capital cost and change the appearance of optimal policies but do not affect the substance of the management problem. In this paper the cases of instantaneous and delayed investment are compared, but primary emphasis is placed on the more realistic delayed investment assumption. To simplify the structure of the model while incorporating a reasonable delay, it is assumed that in any given year the decision regarding next season's optimal capacity must be made before the end of the current season and that full payment for any new investment must be made in the current season.

The fishery management problem involves yearly escapement and investment decisions. The timing of the two decisions depends on the assumption regarding delays in bringing investment online; the following applies to the delayed investment case. Given the recruitment R_n, the optimal escapement S_n^* is chosen, subject to the constraint $R_n e^{-qTK_n} \le S_n^* \le R_n$ where the lower limit is reached by fishing with maximum effort throughout the season. Then, the optimal investment for next year is chosen, subject to $I_{n+1} \ge 0$ and based on the value of S_n^*; payment is made in year n for this new capacity.

The fishery is assumed to face perfectly elastic demand (with given constant selling price p) and linear operating costs (with unit cost of effort c). Yearly rents accruing to the fleet, as a function of recruitment, capacity, escapement, and investment, are then given by

$$\pi(R,K,S,I) = \int_0^T (pqEx - cE)dt - \delta I$$
$$= p(R - S) - (c/q)\log(R/S) - \delta I$$

using $dx/dt = -qEx$, $x(0) = R$, $x(T) = S$. Assuming that the fishery manager desires to maximize the discounted sum of annual fishery rents, our problem can be stated as follows:

$$\underset{(S_1,I_2,S_2,\ldots)}{\mathrm{Max}} \left[\sum_{n=1}^{\infty} \alpha^{n-1}\, \pi(R_n,K_n,S_n,I_{n+1})\right]$$

subject to $R_{n+1} = F(S_n)$, $K_{n+1} = (1-\gamma)K_n + I_{n+1}$, $R_n e^{-qTK_n} \le S_n \le R_n$, $I_{n+1} \ge 0$ where α is the annual discount factor.

The dynamic programming equation for the value of the fishery in state (R_n,K_n) at the start of a season n is given by

$$V(R_n,K_n) = \underset{S_n}{\mathrm{Max}}\ \underset{I_{n+1}}{\mathrm{Max}}\ [\pi(R_n,K_n,S_n,I_{n+1}) + \alpha V(R_{n+1}, K_{n+1})]$$

where $R_{n+1} = F(S_n)$, $K_{n+1} = (1-\gamma)K_n + I_{n+1}$, the outer maximization is subject to $R_n e^{-qTK_n} \le S_n \le R_n$, and the inner maximization is over the range $I_{n+1} \ge 0$. This is simply a statement, using Bellman's (1957) principle of optimality, that the value of the fishery is given by the maximum value of the sum of current rents plus the discounted future value of the fishery, where the escapement and investment levels are chosen from the set of all feasible values. Removing the subscripts on the variables, this can be rewritten as

$$(1)\quad V(R,K) = \underset{R\cdot\exp(-qTK)\le S\le R}{\mathrm{Max}}\ \underset{I\ge 0}{\mathrm{Max}}\ \{\pi(R,K,S,I) + \alpha V[F(S), (1-\gamma)K + I]\}$$

where $\pi(R,K,S,I) = p(R - S) - (c/q)\log(R/S) - \delta I$.

Equation 1 will form the basis for most of the analysis and results presented in this paper. For convenience, a full list and definition of symbols used in this paper follows:

R	Annual recruitment
K	Fleet capacity (capital stock)
S	Annual escapement
I	Annual investment
x	Instantaneous biomass (in-season)
E	Instantaneous fishing effort
$V(R,K)$	Value function
V_R	Partial derivative of V with respect to R
V_K	Partial derivative of V with respect to K
$s(\cdot)$	Target escapement function
$h(\cdot)$	Target fleet capacity function
$F(\cdot)$	Stock-recruitment function
a	Maximum productivity of the fish stock
b	Maximum possible recruitment
m	Instantaneous natural mortality rate
T	Maximum possible season length
q	Instantaneous catchability coefficient
p	Unit market price for "fish"
c	Unit cost of fishing effort
δ	Unit cost of capital
γ	Annual depreciation rate
α	Annual discount factor = $1/(1 + \text{discount rate})$
π	Annual fishery rents
x_0	Bionomic zero-profit biomass level = c/pq

Heuristic Analysis and Numerical Method

To gain qualitative information about the optimal investment and escapement problem, this section begins with an heuristic study of the dynamic programming equation 1. Assume for now that the fish stock displays pure compensatory population dynamics (i.e. a concave increasing stock-recruitment function, as in the Beverton–Holt model) and that $V_R > 0$, $V_K > 0$, $V_{RK} > 0$, and $V_{KK} < 0$ over all nonzero values of R and K for which V is twice differentiable. The latter assumption simply states that more fish and more capital increase the value of the fishery, that more fish are more desirable the larger the capital stock, and that the fishery has decreasing marginal returns to capital.

Optimal Investment

Performing the inner maximization in equation 1, for fixed S, produces the optimality equation for investment:

$$(2)\quad V_K[F(S), (1-\gamma)K + I^*] = \delta/\alpha$$
$$\text{or } I^* = 0 \text{ if } V_K[F(S), (1-\gamma)K] < \delta/\alpha.$$

This states that, unless the fleet is temporarily overcapitalized, next year's optimal capacity, $(1-\gamma)K + I^*$, should be set such that the marginal benefit of an extra unit of capital equals its marginal cost.

Define $K' = h(S)$ as the solution of the implicit equation $V_K[F(S), K'] = \delta/\alpha$. Then, $h(S)$ is next season's optimal capacity, which is an increasing function of escapement by the above assumptions (Charles 1982).

Thus, if $(1-\gamma)K > h(S)$, the optimal investment is $I^* = 0$ (capital is already sufficiently abundant), while otherwise, I^* is chosen so that $(1-\gamma)K + I^* = h(S)$. This can be written as

$$(3) \quad I^*(S,K) = \text{Max}\,[h(S) - (1-\gamma)K,\ 0]$$

so that, in general, investment desired for the next season depends both on capacity and on escapement in the current season.

Optimal Escapement

Inserting $I^*(S,K)$ into equation 1, performing the outer maximization by taking a total derivative with respect to S, and noting that for any S and K either $I^*_S(S,K) = 0$ or $\alpha V_K[F(S),\ (1-\gamma)K + I^*(S,K)] - \delta = 0$, an optimality expression is produced; this equates the marginal benefit and marginal cost of an incremental increase in escapement:

$$(4) \quad \alpha F'(S)\cdot V_R[F(S),\ (1-\gamma)K + I^*(S,K)] = p\left(1 - \frac{x_0}{S}\right)$$

where $x_0 = c/pq$ is the bionomic zero-profit biomass level, and the constraint $Re^{qTK} \le S \le R$ has been neglected temporarily.

Assume that equation 4 implicitly defines a unique function $S = s(K)$, representing the target escapement for a given capacity level, K. Numerical tests indicate that $s(K)$ is indeed a well-behaved single-valued function. In Charles (1982) it is shown that this target escapement increases with the level of the capital stock, approaching the optimal escapement for the more common abundant-capital problem as the fleet capacity becomes large. In other words, for sufficiently large K, $s(K)$ satisfies the "Modified Golden Rule" equation:

$$F'(S)\cdot\frac{1 - x_0/F(S)}{1 - x_0/S} = 1/\alpha.$$

From a particular state (R,K) of the fishery, the feasible escapement S is constrained by $Re^{-qTK} \le S \le R$. Hence, the target $s(K)$ may not always be attainable and the optimal escapement $S^* = S^*(R,K)$ must be defined as follows:

$$(5) \quad S^*(R,K) = \begin{cases} R\cdot\exp(-qTK); & R > s(K)\exp(qTK) \\ s(K); & R \ \text{intermediate} \\ R; & R < s(K). \end{cases}$$

This completes, at least heuristically, the overall synthesis of the optimal harvesting/investment policy in the form of the two policy functions $s(K)$ and $h(S)$, giving the optimal action (S^*, I^*) as a function of the state (R,K). In general terms, the optimal escapement is expected to increase with the current capital stock size, while the optimal fleet capacity desired for next season should increase with the current end-of-season escapement. Given the optimal policies $S^*(R,K)$ and $I^*(S,K)$, the resulting value function is defined implicitly by the equation

$$(1') \quad V(R,K) = \pi(R,K,S^*(R,K),I^*[S^*(R,K),K]) + \alpha V(F[S^*(R,K)],\ (1-\gamma)K + I^*[S^*(R,K),K])$$

which is rather complex in general but simplifies somewhat in special cases (see last subsection under Numerical Results).

To summarize the behavior of the fishery, at the beginning of a season, given recruitment R and capacity K, the fish stock is first harvested down to an escapement $S^*(R,K)$. Then, depreciation and investment occur such that if the depreciated fleet capacity $(1-\gamma)K$ is less than the target capital stock $h(S^*)$, investment brings the capacity to $h(S^*)$ by the start of the next season. The process is then repeated from the new biomass/capacity point $\{F[S^*(R,K)],\ (1-\gamma)K + I^*[S^*(R,K),K]\}$. The resulting trajectories, and their eventual convergence on a long run equilibrium point, are discussed under Numerical Results.

The above heuristic discussion applies to the delayed investment case. If, instead, investment is assumed to occur instantaneously, appropriate modifications must be made to the analysis (see Charles 1982 for details). It is shown there that the only substantial changes are (i) the optimal fleet capacity target becomes a function of the current season's recruitment rather than the past seasons's escapement, $K^* = h(R)$, and (ii) the effective unit capital cost is reduced from δ to $\alpha\delta$, since new investment is now available immediately.

Numerical Method

The heuristic analysis provides the basis for the numerical methods used to solve the dynamic programming problem, equation 1. In particular, optimal management can be summarized in the form of two policy curves, $s(K)$ and $h(S)$ (or $h(R)$), representing the optimal escapement and capacity targets, respectively. The numerical scheme uses a "policy iteration" methodology to derive these optimal control functions. This approach, discussed extensively in Charles (1982), is simply outlined here. First, an initial guess is made for $s(K)$ and $h(S)$, and the value function V corresponding to these policies is calculated. The partial derivatives V_R and V_K are then deduced and inserted into equations 2 and 4; these are used to obtain improved policies $s(K)$ and $h(S)$. The corresponding new value function is determined and the policy improvement algorithm is repeated until suitable convergence to the optimal functions $s(K)$ and $h(S)$ is achieved.

The numerical scheme for accomplishing this policy iteration process requires discretization of the state variables (biomass and capacity) and use of a two-dimensional grid in the biomass/capacity plane. For each pair of policy functions, a set of simultaneous equations is solved for the value function at grid points, and a smooth surface is formed between these points to obtain the partial derivatives V_R and V_K. Linear or cubic interpolation is used where necessary to deduce values lying between the grid points.

The numerical scheme worked well in all cases involving delayed investment. A modified methodology was required when investment was instantaneous; for the two base cases considered under Numerical Results, this revised method performed well when the fish stock was slow-growing but was ill-behaved in the one fast-growing case. Hence, in this latter

TABLE 1. Base case parameter values for the prawn and whale fisheries. The data are adapted from Clark and Kirkwood (1979) and Clark and Lamberson (1982) (cd, catcher day; BWU, blue whale unit; A$, Australian dollars).

Quantity	Prawn fishery[a]	Whale fishery
"Fish" price (p)	0.9 A$·kg^{-1}	7000 US$·BWU^{-1}
Variable cost (c)	1600 A$·wk^{-1}·vessel^{-1}	5000 US$·cd^{-1}
Capital cost (δ)	0.47×10^6 A$·vessel^{-1}	10000 US$·cd^{-1}·yr^{-1}
Depreciation rate (γ)	0.15	0.15
Discount factor (α)	0.9	0.9
Catchability (q)	0.00179·wk^{-1}·vessel^{-1}	1.3×10^{-5}·cd^{-1}
Max. season length (T)	26.0 wk	1.0 yr
Nat. mortality rate (m)	0.05·wk^{-1}	0.1·yr^{-1}
Max. productivity (a)	42.0	1.15
Max. recruitment (b)	7.0×10^6 kg	1.186×10^7 BWU

case, results reported here are approximate (but do in fact reflect the qualitative behavior deduced in this section).

Numerical Results

A full analysis of the deterministic investment and escapement model embodied in equation 1 can now be provided. Numerical results are based on two fisheries: (i) the Australian Gulf of Carpenteria banana prawn fishery (Clark and Kirkwood 1979) and (ii) the aggregated pelagic whaling fishery (Clark and Lamberson 1982).

The available data for these fisheries have been somewhat simplified to fit the present model and to emphasize the optimal investment problem. In the prawn fishery, a homogeneous fleet is assumed, an average prawn weight used in lieu of intraseasonal growth, and natural mortality is constrained to occur during the off-season. The whaling data used by Clark and Lamberson (1982) have been converted from continuous- to discrete-time and, as in the continuous-time case, delays in recruitment are neglected (cf. Clark 1976).

The stock-recruitment function $F(S)$ is given by $R = F(S) = aS/(1 + aS/b)$ or $R = F(S) = aS\cdot e^{-aS/eb}$ for the Beverton–Holt and Ricker cases, respectively, where S is the escapement after fishing has taken place. The maximum possible recruitment, b, for the prawn fishery is set equal to the sample mean of recruitment data from G. P. Kirkwood (C.S.I.R.O. Division of Fisheries, Cronulla, Australia, personal communication). The maximum rate of growth, or productivity, of the prawn stock, a, is set arbitrarily at the moderately high base value of $a = 42$.

The data used for each fishery are presented in Table 1. If S is the escapement after fishing, Se^{-mT} is taken to be the end-of-year escapement after both fishing and natural mortality. An examination of the stock-recruitment functions indicates that the factor e^{-mT} can be directly incorporated by changing the value of a given in Table 1 to ae^{-mT}; hereafter, the stated value of a is always first transformed to ae^{-mT} before being inserted in the stock-recruitment function $F(\cdot)$. (Note that although the results presented below are based on two fisheries and two stock-recruitment functions, they are in fact quite general. With the choice of the Beverton–Holt or Ricker function, one can capture the qualitative features of most fisheries, and by varying the parameters in the two base case fisheries, arbitrary economic and ecological conditions can be considered.)

It will be of interest to compare optimal investment policies with the open-access scenario resulting from uncontrolled fisheries development. Assuming that in the open-access case investment continues until the average net revenue (per unit capacity) just covers the unit capital cost, then in equilibrium:

$$\frac{\alpha}{1-\alpha}\cdot\frac{\pi(R,K,S,I)}{K} = \delta$$

where the left-hand side represents the total present value of discounted rents, per unit of capital. Setting $I = \gamma K$ to hold the capital stock constant in equilibrium, and assuming full utilization of the fleet, this can be written as

$$\frac{\alpha}{1-\alpha}\cdot[p(R-S)/K - cT - \gamma\delta] = \delta$$

with $R = F(S) = Se^{qTK}$. This simplifies to

$$\frac{(e^{qTK}-1)S}{K} = \left[\left(\frac{1-\alpha}{\alpha} + \gamma\right)\delta + cT\right]\Big/p.$$

Solving this equation simultaneously with the equilibrium condition $F(S)e^{-qTK} = S$ produces the open-access equilibrium capital stock and biomass.

If Beverton–Holt stock recruitment is assumed, so that $F(S) = aS/(1 + aS/b)$, this solution can be simplified. In equilibrium, $F(S)/S = a/[1 + (aS/b)] = e^{qTK}$, so that $S = (b/a)(ae^{-qTK} - 1)$. Hence, the open-access capacity can be restated as the solution of the equation

$$(6)\quad (b/a)(ae^{-qTK}-1)(e^{qTK}-1)/K = \left[\left(\frac{1-\alpha}{\alpha} + \gamma\right)\delta + cT\right]\Big/p.$$

This equation can be solved iteratively for the optimal fleet capacity K and is applied below.

INSTANTANEOUS INVESTMENT CASE

Interpretation of the results is facilitated by comparing with those obtained by Clark et al. (1979), who assumed that

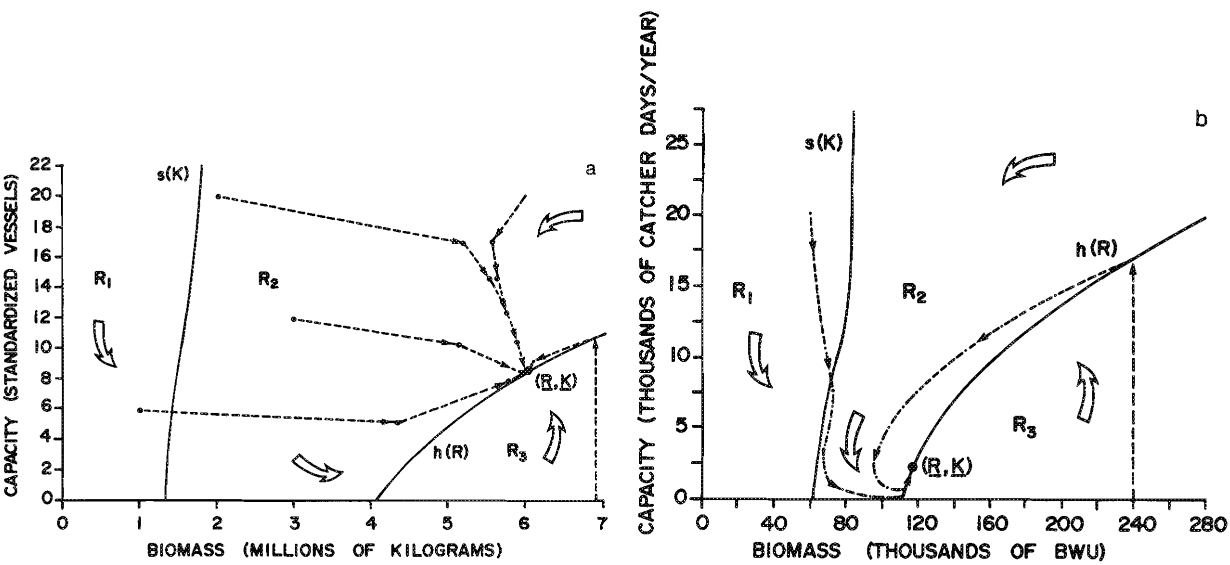

FIG. 1. Optimal capacity function, $h(R)$, and optimal escapement function, $s(K)$, for (a) the base case prawn fishery and (b) the base case whale fishery, with instantaneous investment. Large arrows indicate the overall effect of fishery dynamics. Sample trajectories and the long-run equilibrium $(\underline{R},\underline{K})$ are also shown.

investment occurs instantaneously. Figure 1 here is precisely the discrete-time analogue of the Clark et al. (1979) results (in particular their fig. 2), and the $s(K)$ and $h(S)$ curves correspond closely with their switching curves, σ_1 and σ_2, respectively. As expected, both $s(K)$ and $h(S)$ are increasing functions, $h(S)$ is concave, and $s(K)$ approaches a maximum value at large fleet capacities. To the left of the $s(K)$ curve, in region R_1, neither harvesting nor investment is desirable. In region R_2, harvesting should take place, reducing the fish stock towards the target escapement curve $s(K)$, or as close as possible to that escapement given the level of capacity available. However, as long as the fishery is in region R_2, no new fleet investment should be undertaken. If $K < h(R)$, so that the fishery lies in region R_3, immediate investment should occur until $K = h(R)$, and thereafter, harvesting should reduce the fish stock towards the $s(K)$ curve.

A sampling of possible trajectories is shown in the figure. Note that all trajectories eventually converge on a single long-run equilibrium point $(\underline{R},\underline{K})$ given in terms of recruitment and capacity (after depreciation and reinvestment). The equilibrium point corresponds to the point (x^*,K^*) in Clark et al. (1979) and represents the optimal equilibrium in the case where capital is perfectly malleable but not "abundant," so that the rental cost of capital must be included in variable costs. This is discussed in more detail in Charles (1982). Unlike in the Clark et al. (1979) model, this equilibrium point is not apparent from examining the $K = h(R)$ policy curve alone. In the continuous-time case, when a trajectory reaches the biomass level $x = x^*$, below (x^*,K^*), the optimal policy is an instantaneous investment to the capacity level $K = K^*$, thereafter remaining at (x^*,K^*). In discrete time, however, trajectories tend to "jump" across the line $R = \underline{R}$ rather than touch it smoothly, so the use of a single final impulse control at $\underline{R}$ is not a feasible method to reach the equilibrium point.

Furthermore, whereas equilibrium is reached in finite time with the continuous-time model, in a discrete-time situation the approach to equilibrium is asymptotic. The more gradual approach to equilibrium in discrete-time seems to reflect the benefit of incrementally increasing fleet capacity as the biomass grows, to take advantage of limited intraseasonal harvesting.

Apart from the differences mentioned above, the behavior of this instantaneous investment model and that of Clark et al. (1979) are quite similar, due to the pure compensatory nature of both the Beverton–Holt function and the continuous-time growth function used by Clark et al. (1979).

Delays in Investment

As discussed under The Model, the introduction of delayed investment produces little change in the desired escapement and capacity in any given year, except inasmuch as payment for the new capacity must be made earlier than would be the case for instantaneous investment, and hence, effective capital costs are higher. However, management implications and the appearance of the optimal policies can differ substantially, since optimal capacity is now given as a function of escapement rather than recruitment.

Figure 2 depicts the optimal policies for the prawn fishery, with delayed investment, but otherwise unchanged parameters. With this fast-growing stock, a low escapement this year can still produce a large recruitment next year. Hence, it may be optimal to plan and pay for investment this year, even though stocks seem low, in the knowledge that when this new capacity becomes available next season, it can be used to harvest a much larger fish stock. This can lead to the situation shown in region R_4 of Fig. 2, where positive investment is optimal even though a harvesting moratorium is in place.

When such a situation arises, optimal escapement $s(K)$ must be independent of fleet capacity at low capital stocks (as

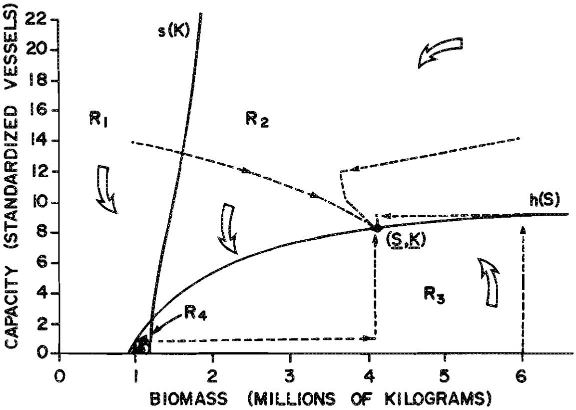

FIG. 2. Optimal policy functions for the base case prawn fishery with delayed investment. Sample trajectories and the long-run equilibrium ($\underline{S},\underline{K}$) are indicated.

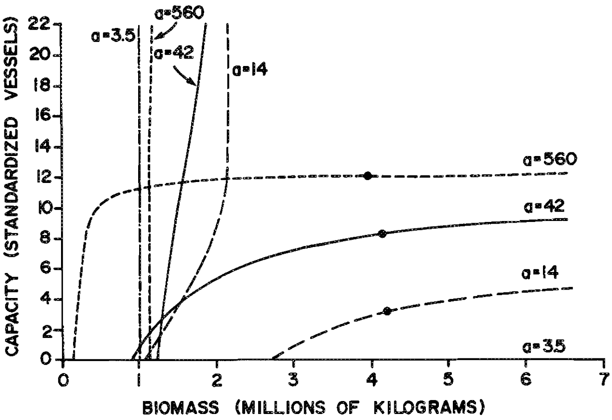

FIG. 3. Effect of prawn stock productivity on the optimal policy functions. Long-run equilibrium points for each parameter value are indicated.

in Fig. 2). Intuitively, the rationale for this is as follows. If, for a given escapement S, the current capacity is relatively low, investment will take place up to the capacity level $h(S)$, a level dependent solely on the escapement. Next year's recruitment, $F(S)$, is also dependent on the escapement. Hence, in such circumstances, current capacity is irrelevant to the determination of optimal escapement, which is therefore independent of K. Apart from this effect, however, the introduction of delays in investment does not change the $s(K)$ curve significantly.

It can be shown that for a fishery based on a slow-growing stock (whales), little qualitative change in the $h(S)$ curve is noticeable between the instantaneous and delayed investment cases; the policy curves in Fig. 1b remain essentially unchanged with the introduction of delays in investment.

In both the prawn and whale fisheries, trajectories again approach a long-run equilibrium, which can be compared with the corresponding open-access results obtained using equation 6. For the prawn fishery, the open-access capacity, 16.8 standardized vessels, is roughly double the optimal level. In the whale fishery, however, equilibrium biomass is very sensitive to the capital stock. Hence, the open-access and optimal capacities cannot differ by much; in fact, the values turn out to be very close, at 2505 and 2250 catcher days/yr, respectively. These results indicate that the extent to which open-access conditions produce overinvestment can vary considerably. Of course, the actual open-access investment behavior may be quite complicated, so that the present model only approximates the true situation.

Productivity and Carrying Capacity of the Resource

Using the Beverton–Holt stock-recruitment function $R = F(S) = a^*S/(1 + a^*S/b)$, with $a^* = ae^{-mT}$, the maximum productivity (intrinsic growth rate) is $F'(0) = a^* = ae^{-mT}$. As a increases, holding the maximum recruitment b constant, recruitment becomes less and less dependent on escapement. One would expect that the higher the growth rate of the stock, the better off the fishery and hence the higher is the optimal capacity. This is confirmed for the prawn fishery in Fig. 3, where optimal policy functions are shown for each of $a = 3.5$, 14, 42, and 560, with $b = 7.0 \times 10^6$ fixed.

With $a = 3.5$, actual productivity is $ae^{-mT} = 0.95 < 1$, so the stock size will decline towards extinction even without fishing. Not surprisingly, a zero investment level is optimal in this case, but if for some reason fleet capacity is already in place, harvesting should occur down to the zero-profit level $s(K) = x_0 = 1.0 \times 10^6$. The optimal policy functions for the case $a = 14$ resemble those of the relatively low-productivity whale fishery, while $a = 42$ corresponds to the base case prawn fishery. As productivity increases, the $h(S)$ optimal capacity curve continues to shift upwards. The limiting case where recruitment is independent of escapement is approximated here by setting $a = 560$; the optimal capacity curve is fairly flat, with $h(S) \simeq 12$, for all but the lowest escapements.

The optimal escapement at low fleet capacity decreases steadily towards x_0 with a declining biomass growth rate. This confirms the idea that with a slow-growing stock and a low level of capacity one has little incentive to conserve the current stock, which will decline towards a low long-run equilibrium even without fishing. On the other hand, at high capacity levels K, the optimal escapement $s(K)$ depends on the intrinsic growth rate in a rather complicated way (see Fig. 5). As before, $s(K) \simeq x_0$ if productivity is very low, but with increases in the growth rate, the reproductive potential of the stock is improved, and higher escapements $s(K)$ are desirable. Ultimately, however, at high productivity, recruitment becomes less dependent on escapement, so that the optimal escapement $s(K)$ can be reduced, increasing immediate benefits with little effect on future stocks.

The maximum recruitment level, b, serves as a suitable indicator of the carrying capacity of a fish stock with Beverton–Holt dynamics. The value $b = 7.0 \times 10^6$, used in the base case, was derived from the sample mean of recent prawn recruitment data and has been substantially revised and extended from that used in the analysis of Clark and Kirkwood (1979): their older data produce the value $b = 11.3 \times 10^6$. The optimal policies based on each of these carrying capacity values, with productivity set at $a = 42.0$ in both cases, indicate that revising the data produces substantial movement in

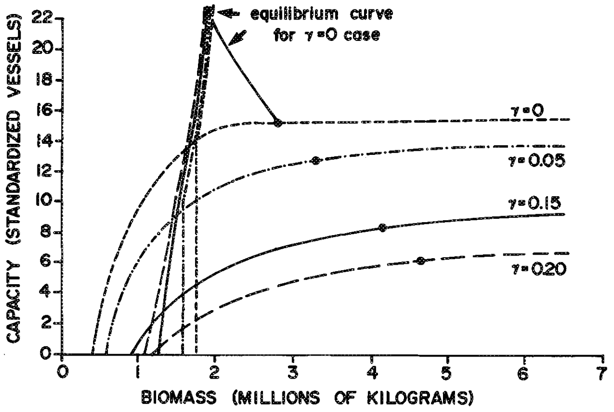

FIG. 4. Role of depreciation in the base case prawn fishery. The zero-depreciation equilibrium curve is shown, together with equilibrium points corresponding to $\gamma = 0.05, 0.15$, and 0.20.

both optimal policy functions. The optimal equilibrium capacity declined from 14.5 to 8.2 if the new data are used in place of the old (see Charles 1982 for further details). This relative decrease in optimal capacity holds also when higher values of productivity, such as $a = 560$, are considered.

In summary, the productivity and carrying capacity of the fish stock can have substantial effects on the optimal policies, in particular the optimal capacity function. This is especially of interest in such cases as the banana prawn fishery, where little is known about the stock-recruitment relationship. Dealing with parameter uncertainty in these fisheries becomes an important problem for further research.

DEPRECIATION RATE

The value of the depreciation parameter, $\gamma = 0.15$, used by Clark and Lamberson (1982) was utilized in the base case runs for both the prawn and the whaling fisheries. In a capital investment model, it is of interest to examine the effect on optimal policies of variations in the depreciation rate.

The results for the prawn fishery (Fig. 4) are intuitively appealing. A decrease in the depreciation rate leads to an upward shift in the investment curve $h(S)$, reflecting the increased life and hence the increased value of a new unit of capacity. On the other hand, an increase in γ increases the desire to use capacity before it depreciates, leading to a shift in the $s(K)$ curve to lower escapements. This latter shift is less pronounced at high capacity values, where capital is relatively abundant in the "near future" even for $\gamma = 0.20$.

With no depreciation ($\gamma = 0$), capacity K can never decrease. Charles (1982) showed that the set of points (S,K) that satisfy $S = \mathrm{Max}\,[s(K), F(S)e^{-q\tau K}]$ and that lie above the curve $K = h(S)$ form an equilibrium curve upon which all trajectories will converge. However, in the particular case of Fig. 4, the optimal capacity curve $h(S)$ is very flat for sufficiently large escapement levels. Hence, if the capital stock is initially low, fishery dynamics will be such that investment will occur up to the equilibrium level $K \simeq 15$. Thereafter, the biomass will adjust so as to approach the long-run equilibrium point on the $\gamma = 0$ optimal capacity curve.

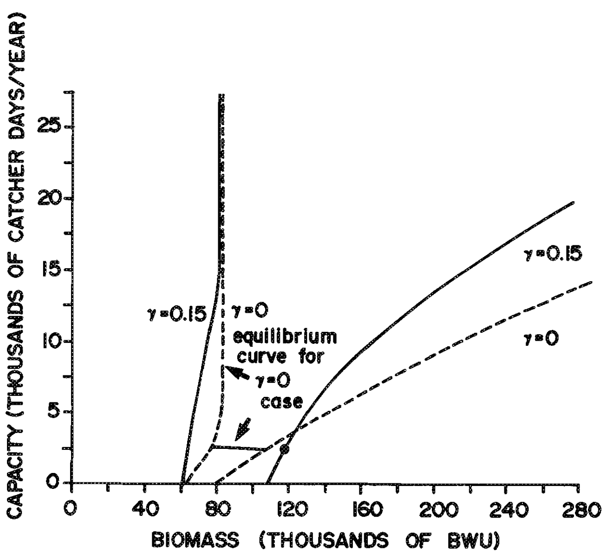

FIG. 5. Role of depreciation in the whale fishery. The equilibrium point for the $\gamma = 0.15$ case and the equilibrium curve for the $\gamma = 0$ case are shown.

For the whale fishery (Fig. 5) the variation of the $s(K)$ curve with γ is qualitatively similar to that of the prawn fishery. In the $\gamma = 0$ case, the long-run equilibrium will again lie somewhere on the equilibrium curve, above the curve $K = h(S)$. However, the optimal capacity curve is now sufficiently steep that if the fishery has a low initial capital stock, a wide range of equilibrium points may be reached, depending on the initial recruitment value.

The unusual aspect of these whaling fishery results is the intersection of the $h(S)$ investment curves derived for the two levels of depreciation and, in particular, the fact that for sufficiently large biomass levels, the optimal capacity level is higher with depreciation than without. As described above, one might expect that if a unit of investment is profitable, given a relatively high depreciation rate, then that same unit of investment is even more desirable if it is longer lasting (in the absence of depreciation). Indeed, this is the case with the prawn fishery results above.

This counterintuitive result can be explained by considering the interaction of two key fishery parameters, the biological productivity (a or $a \cdot e^{-mT}$) and the relative cost of capital (δ/cT). The latter is a measure of the fishing fleet's capital intensity, being the ratio of unit capital costs, δ, to maximum yearly unit variable costs, $c \cdot T$ (the quantity δ/cT is discussed further in Charles 1983). For the prawn fishery, the effective intrinsic growth rate is $ae^{-mT} = 11.45$, while the cost ratio is $\delta/cT = 11.3$. In the whale fishery, $ae^{-mT} = 1.04$ and $\delta/cT = 2.0$. Hence, both the resource productivity and the relative cost of capital differ considerably between the two fisheries. Modifying the prawn fishery by simultaneously reducing the productivity to $a = 14$ ($ae^{-mT} = 3.82$) and reducing the capital cost so that $\delta/cT = 2.0$ (implying $\delta =$ \$0.0832 million), optimal policies qualitatively similar to those of the whale fishery are obtained (Fig. 6).

An analysis of trajectories for the policy functions of Fig. 6

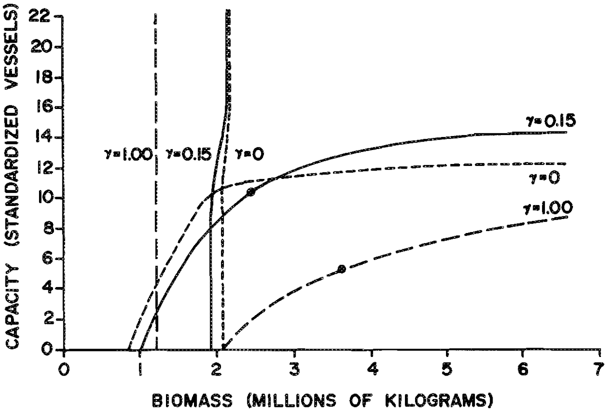

FIG. 6. Effect of the depreciation rate on a prawn fishery with low productivity ($a = 14$) and low capital cost (δ = A\$0.0832 million).

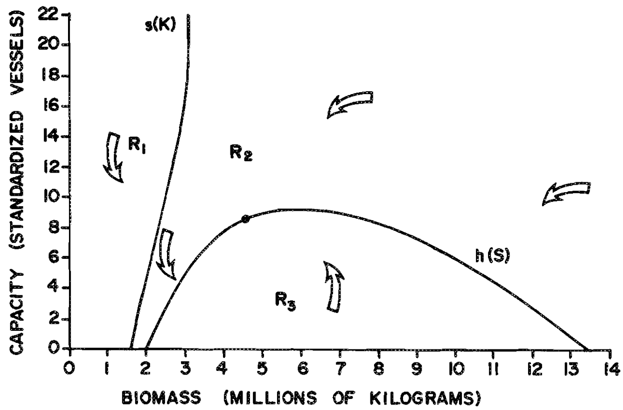

FIG. 7. Optimal policy functions for a fishery with a Ricker stock-recruitment function (a = 11.639, b = 7.0 × 10^6) (see text for details).

indicates that the relative heights of the $\gamma = 0$ and $\gamma = 0.15$ optimal capacity curves are determined not simply by the ratio δ/cT but rather by a more complicated comparison of the present values of investment costs versus fishery rents. The zero-depreciation $h(S)$ curve represents a balance between investment costs and the natural preference for a larger capital stock to enable more rapid accumulation of rents as the stock is harvested down to equilibrium. Depreciation introduces two new factors: (i) the need for future investment to overcome depreciation and (ii) the desire to "beat" depreciation by harvesting the stock before the fleet "wears out." It is this latter effect that appears responsible for the $\gamma = 0.15$ $h(S)$ curve lying above the corresponding zero-depreciation curve at high escapement levels. However, as depreciation increases beyond 15%, the optimal capacity curve drops as the yearly costs of overcoming depreciation predominate. When $\gamma = 1.00$, so that vessels last for only one season, the $h(S)$ curve lies completely below its zero-depreciation counterpart. This rather complicated response to the depreciation rate seems to depend critically on actual parameter values, necessitating careful treatment of the data in specific applications. Nevertheless, an examination of the intrinsic growth rate, a, and the ratio of capital to operating costs, δ/cT, provides a useful indication of the role that depreciation might play in a particular fishery.

Capital Cost, Fish Price, and Discount Rate

This section summarizes results concerning the sensitivity of optimal investment and escapement levels to unit capital costs (relative to operating costs), selling price, and discount rate (for further details see Charles 1982).

The effects of changes in the unit capital cost, with unit variable cost (c) fixed, have been examined for the base case ($a = 42$) prawn fishery and for an $a = 14$ (lower productivity) prawn fishery. In the former case, a halving of the capital cost resulted in a 1.7-fold increase in equilibrium capacity. In the latter case, a reduction to almost one-sixth the usual capital cost, from \$0.47 million to \$0.0832 million, produces a 3.5-fold increase in the equilibrium capacity (with $\gamma = 0.15$). In both cases, optimal escapement at low capacities increased as capital cost decreased, reflecting the increased benefit in saving more of the fish stock for the future, at which time capacity will be higher.

The variation of the optimal policy functions with fish price was examined for the $a = 42$ prawn fishery. A doubling of the price, from its actual level of \$0.9·kg^{-1} to \$1.8·kg^{-1}, produced more than a doubling in equilibrium capacity, while a halving of the price made investment entirely uneconomic, so that depreciation slowly reduces the fleet size to zero. However, harvesting still takes place in this low-price case, as long as $R > s(K)$, although the escapement target $s(K)$ has increased relative to the base case.

Optimal policy functions have been obtained for the $a = 42$ prawn fishery with discount factors (and corresponding discount rates) of $\alpha = 0.99$ (1%), 0.90 (11%), and 0.8 (25%). Naturally, the lower the rate of discounting, the higher the benefit from investing in capacity for the future (to become available next year) and the higher the desired escapement, $s(K)$, to be left at the end of the current season. While optimal escapements (for fixed K) increase with α, the equilibrium escapement decreases with α, reflecting the optimality of using the increased capacity that becomes available with low discounting.

Ricker Stock-Recruitment

Results presented to this point have been based on the Beverton–Holt stock-recruitment function. In this section, these are compared with results obtained using the Ricker form, $R = F(S) = aS \cdot e^{-aS/eb}$, which has the property that recruitment attains a maximum value of $R = b$ at $S = eb/a$, and thereafter declines roughly exponentially. Since the fleet capacity target $K = h(S)$ is determined from the equation $V_K[F(S),K] = \delta/\alpha$, it would be expected that the optimal capacity will follow the qualitative behavior of the stock-recruitment function $F(S)$, in this case initially increasing to a maximum and thereafter decreasing.

Numerical results (Fig. 7) confirm this expectation. The parameters of the Ricker function used in this example, namely $a = 11.639$ and $b = 7.0 \times 10^6$, were chosen so that the maximum recruitment is identical to that of the

TABLE 2. Optimal value function $V(R,K)$ for the base case prawn fishery. Recruitment is given in millions of kilograms, capacity in standardized vessels, and value in millions of Australian dollars.

	Recruitment						
Capital	1.0	2.5	4.0	5.5	7.0	8.5	10.0
0	3.2	3.4	3.5	3.6	3.7	3.7	3.7
2	4.0	4.3	4.6	4.8	4.9	5.1	5.2
4	4.8	5.2	5.5	5.8	6.1	6.4	6.6
6	5.5	6.0	6.5	6.9	7.3	7.7	8.0
8	6.3	6.9	7.4	7.9	8.4	8.9	9.3
10	7.0	7.6	8.3	8.9	9.5	10.0	10.6
12	7.7	8.4	9.2	9.9	10.5	11.1	11.8
14	8.4	9.1	9.9	10.7	11.5	12.2	12.9
16	9.0	9.7	10.6	11.5	12.3	13.1	13.9
18	9.5	10.3	11.3	12.2	13.1	14.0	14.8
20	10.1	10.9	11.8	12.8	13.8	14.7	15.6
22	10.5	11.4	12.3	13.4	14.4	15.4	16.3
24	10.9	11.8	12.7	13.8	14.9	15.9	16.9
26	11.3	12.2	13.1	14.2	15.3	16.4	17.5
28	11.6	12.6	13.5	14.5	15.7	16.8	17.9

Beverton–Holt form for the base case prawn fishery and occurs at $S = 6.0 \times 10^6$ (to produce a reasonable agreement with the Beverton–Holt curve for low and medium escapements). Other model parameters are unchanged from those given in Table 1 for the prawn fishery, and delayed investment is assumed.

Note that there is a threshold level of escapement and hence of $F(S)$, below which no investment occurs. At high escapements, $F(S)$ decreases and eventually drops below its threshold value; thereafter, a zero fleet size would be preferred, at least temporarily (the horizontal scale in Fig. 7 has been changed from that used in previous results to include this upper cutoff). The optimal escapement curve $s(K)$ behaves similarly to those of Beverton–Holt cases, except the optimal high-capacity escapement has substantially increased, reflecting reduced productivity at low escapements for this particular Ricker curve.

VALUE FUNCTION

To this point the optimal policy functions, $s(K)$ and $h(S)$, have been derived and studied under various assumptions and parameter combinations. However, the dynamic programming approach produces not only the optimal policies but also the optimal value function. Indeed, for any policies $s(K)$ and $h(S)$, the corresponding value function is the solution of equation 1′, with $S^*(R,K)$ and $I^*(S^*,K)$ depending on $s(K)$ and $h(S^*)$ through equations 5 and 3, respectively.

A sample value function, corresponding to the optimal policy functions for the base case prawn fishery, is represented in Table 2, which shows that for Beverton–Holt population dynamics, $V_R > 0$, $V_K > 0$, $V_{RK} > 0$, and $V_{KK} < 0$ throughout the $R-K$ range considered; this is consistent with the assumptions made under Heuristic Analysis and Numerical Method. At low levels of the capital stock, the value function is quite insensitive to the level of recruitment, R. This reflects the fact that, with low fleet capacity, increased recruitment has little effect on rents for the current season, and since the prawn stock is fast-growing, differences in this year's stock size tend to substantially disappear by next year. At sufficiently high capacity levels, the target escapement can be attained from a wide range of recruitment values. For such (R,K) combinations, $V(R,K) = pR - (c/q) \log (R) + W(K)$, and hence, changes in V due to variations in R can be easily calculated within this range. Numerical results shown in Table 2 agree with such analytic calculations.

Discussion

In the instantaneous investment case, results obtained here correspond closely to those of Clark et al. (1979), the primary difference between the seasonal and continuous-time models being the more gradual approach to equilibrium in the discrete-time case. The important conclusion of Clark et al. (1979) regarding the optimality of "a complex pattern of expansion, overcapacity, and gradual contraction via depreciation" towards an "optimal sustained yield" equilibrium holds for the present seasonal model as well.

As in Clark et al. (1979), optimally managed fisheries will tend to move between three primary regimes: (i) a high-biomass, low-capacity regime, with both harvesting and investment being desirable, (ii) a high-biomass, high-capacity situation, in which investment is unwarranted but harvesting takes place, and (iii) a low-biomass case in which the fishery is essentially shut down, with neither harvesting nor investment being desired.

The introduction of delays in investment, as well as adding further realism to the model, produces the possibility of a fourth management regime in which the resource stock is too low to permit harvesting but is expected to recover during the "investment delay" period. In such cases, planning and payment for investment becomes desirable when current capacity is sufficiently low. Assuming linear variable costs and a present value rent maximization objective, optimal management was found to be characterized by capacity and escapement target curves, $h(S)$ and $s(K)$, representing the optimal capacity for given escapement S and the optimal escapement for a given fleet capacity K, respectively.

The optimal capacity function proved to be particularly sensitive to the fish price and stock-recruitment parameters, indicating the potential importance of including parameter uncertainty in the analysis. Variations in the depreciation rate produced rather complicated effects, depending both on the magnitude of unit capital costs (relative to operating costs and other economic factors) and on the actual values of the depreciation rate being considered. It was suggested that if capital is relatively inexpensive and if the depreciation rate is positive but not too large, the optimal capacity at high stock sizes can be greater with depreciation than without. This result runs counter to the usual idea that depreciation, as a type of fishing cost, should lead to lower investment. It appears to be caused by a dynamic disequilibrium incentive to harvest the resource quickly, before the fleet "wears out."

In the case of Ricker stock-recruitment, the optimal capacity function adopted an appearance mimicking that of the stock-recruitment curve itself, increasing rapidly at low escapements and declining relatively slowly at higher escapements. This effect is due to the delay in bringing new investment online; desired capacity for next season depends on the current escapement, acting through the reproduction function $F(S)$. This property can be used to predict roughly the qualitative appearance of optimal investment curves based on other stock-recruitment relationships.

While numerical results have been obtained here for two specific fisheries, the methodology and the qualitative results can be expected to apply in many fisheries, as well as in forestry and agricultural investment problems. It is clear from both qualitative and quantitative results presented here that a full analysis of renewable resource management must include questions of optimal investment strategies. Indeed, for many of the cases examined, the investment aspect is substantially more complex than the more widely studied optimal harvesting problem.

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