STAFF PAPER SERIES

PRIVATE AQUACULTURE AND COMMERCIAL FISHERIES:
AN EXPANDED TREATMENT OF THE BIOECONOMICS
OF SALMON RANCHING

James L. Anderson
Department of Resource Economics
University of Rhode Island
Kingston, RI 02881

September 1984

DEPARTMENT OF RESOURCE ECONOMICS

College of Resource Development
University of Rhode Island
Kingston, Rhode Island

85-05

PRIVATE AQUACULTURE AND COMMERCIAL FISHERIES: AN EXPANDED TREATMENT OF THE BIOECONOMICS OF SALMON RANCHING

James L. Anderson
Department of Resource Economics
University of Rhode Island
Kingston, RI 02881

September 1984

Agricultural Experiment Station Contribution # 2277

Abstract

This paper shows that common property problems associated with open access salmon ranching in the absence of a commercial fishery result in inefficiency characterized by overstocking. The presence of an open access fishery presents additional common property problems which will inhibit the development of fish ranching. At prices where salmon ranching does occur, the open access commercial fishery will tend to overexploit the natural fish stock to a greater extent than if there were no salmon ranching. It is shown that there exists a range of prices where both fish stocks can coexist with open access. However, there is a limit price above which the natural stock will be driven to extinction through overfishing stimulated by stock from salmon ranchers. The range of prices under which both species can coexist can be increased through either restrictions of fishery effort or reducing the catchability of aquacultured stock. Cooperative management of both aquaculture and commercial fishing results in profits from both activities and will not cause extinction of the natural fish stock.

Introduction

The role of private aquaculture of salmon has recently become a highly debated issue in the Pacific Northwest. The controversy revolves around a particular type of aquaculture: salmon ranching. The process entails (a) the hatching and raising of salmon to juveniles in confinement (ponds and raceways), (b) the acclimation and release of salmon to the open ocean, and (c) the return of surviving adult salmon to the facility for harvesting and breeding [1]. When the salmon are in the ocean, they interact with the natural fishery in two ways. First, the aquacultured fish are a component of the commercial fishery catch. Second, the aquacultured fish may compete with natural fish for the resources. Conflicts arise. For example, the size of the fishermen's catch can influence the return to the salmon rancher. Alternatively, the salmon rancher's stocking rate influences the fishermen's catch and may indirectly modify natural stock level. In addition to these public resource management problems, the fishermen seem to fear market competition and the potential influence of the salmon ranchers on regulation. Entrance into the salmon ranching business by large corporations such as Weyerhaeuser, Campbell's Soup and British Petroleum has accentuated these fears. Releases of privately reared coho smolts in Oregon, for example, have increased from 88 thousand in 1974 to 23.9 million in 1981 [2]. The number of private releases in 1981 is five times more than the publicly released coho smolts on the Oregon coast [3]. For a more detailed exploration of the underlying political and economic controversy on Pacific Northwest salmon ranching, the reader is referred to work by Stokes [4], and for additional background on salmon management see Crutchfield and Pontecorvo [5].

This paper will present a model of salmon ranching aquaculture. The primary objective is to evaluate the impact of aquacultural development on fish stock, fish supplies and prices under selected market and policy conditions.

1. Salmon Ranching

To clarify the basic features of the aquaculture sector, the initial model presented ignores the existence of a natural fishery or competing fish stock. The salmon rancher's profits are assumed to be a function of the price and costs of harvesting the returning adult salmon and the costs of spawning and raising salmon smolts for ocean release. A general representation of a salmon rancher's profits is

$$\pi_{At} = (p-c_1)H_tW_t - c_2\delta(W_t-H_tW_t) \tag{1.1}$$

where π_{At} are the profits in time t

p is the price received per unit at harvest (assumed constant)

c_1 is the cost per unit at harvest (assumed constant)

c_2 is the cost per smolt released (assumed constant)

δ is a constant relating adults allowed to spawn to smolts released (assumed constant)

W_t is the aquaculture fish recruitment in t

H_t is the salmon rancher's harvest rate in t

$W_tH_t = y_{At}$ is the harvest of returning salmon in t

$W_t-W_tH_t = P_t$ is the parent stock allowed to spawn in t resulting in future smolt release and

$\delta(W_t-W_tH_t) = S_t$ is the smolt release in t.

The first term in the profit function $(p-c_1)H_tW_t$ is the net revenue from harvest. One would expect the cost of harvest c_1 to be small relative to the cost of other traditional fishing harvest methods for salmon because the homing instinct of salmon results in the return of the adults to the original release site. The returns are simply netted from holding facilities.

The cost of aquaculture production is given by the second term $c_2\delta(W_t-H_tW_t)$. The parent spawn stock, P_t, is the total recruitment (total returning adults) minus those harvested. This assumes there is no outside source of eggs or smolts. The salmon aquaculturalist must depend on adult returns for the continuance of the operation. Salmon which are used in spawning have little or no market value.

Once released to the open ocean, the return of adult salmon will depend on the number of smolts released and the natural mortality. The population dynamics of the aquacultured salmon stock, after release to the ocean, are assumed to follow the Beverton-Holt stock recruitment model [6].

$$W_{t+n} = \frac{\delta(W_t-H_tW_t)}{a+b\delta(W_t-H_tW_t)} \qquad (1.2)$$

$$W_{t+n} = \frac{\delta(P_t)}{a+b\delta(P_t)} = \frac{S_t}{a+b\ S_t} \qquad (1.2a)$$

where W_{t+n} is the recruitment of adult salmon in t+n

a and b are constants and

n is the generation time length.

Note that when $\delta = 1$ and $n = 1$

$$\lim_{s\to\infty} W_t = \frac{1}{b},$$

$$W_{t+1} = S_t \text{ when } S_t = \frac{1-a}{b},$$

maximum sustainable recruitment is

$$W_{msy} = \frac{1-\sqrt{a}}{b}$$

and smolt release for maximum sustainable recruitment is

$$S_{msy} = \frac{\sqrt{a}-a}{b} .$$

Without loss of generality, throughout the paper the coefficient δ and the generation length, n, are standardized to equal one. It should be recognized that the results to be presented in this paper are qualitatively the same for all stock recruitment models, f(z), which are continuously differentiable and for which $f'(z) > 0$ and $f''(z) < 0$ for all z. It is also assumed that the open access conditions represent the aggregation of n identical firms.

(A) Open Access (Competitive) Aquaculture:
No Natural Fishery.

The conditions for open access equilibrium from equation (1.1) are:

$$\pi_A = 0 = (p-c_1)H_tW_t - c_2(W_t - HW_t) \tag{1.3}$$

and

$$W_{t+1} = W_t = \frac{W_t - H_tW_t}{a+b(W_t - H_tW_t)} . \tag{1.4}$$

Solving for H and W respectively from (1.3) and (1.4) results in

$$H = \frac{c_2}{p-c_1+c_2} \tag{1.5}$$

and

$$W = \frac{1}{b} - \frac{a(p-c_1+c_2)}{b(p-c_1)} . \tag{1.6}$$

Therefore, equilibrium harvest supply, $HW = Y_A$, is given by

$$Y_A = \frac{c_2}{b(p-c_1+c_2)} - \frac{ac_2}{b(p-c_1)} . \tag{1.7}$$

Figure 1a,b,c shows the open access solution for H, W and Y_A as a function o p. The salmon rancher will not operate if $p < c_1 - \frac{c_2 a}{1-a}$. The open access supply for ocean ranching (Figure 1a) has the same characteristic shape as that of the open access fishery [7]. The reason for this shape is different from the open access fishery case. As the price increases, the salmon ranch decreases harvest effort, thereby increasing the number of spawners. Therefore W increases, approaching $\frac{1-a}{b}$. In the natural fishery, fishing effort is increased with price which decreases the fish stock.

Why will harvest rate decrease with increased price? This is a consequence of open access to the common property ocean stage of salmon development. Assume the system is in equilibrium at some price. If a new, higher price appears, all the aquaculturalists are making positive profits. Therefore, under open access, entrance of competitors or expansion of existing salmon ranches is expected. At the new price, a firm can enter with a lower harvest rate (higher smolt release rate). If the original salmon ranchers do not reduce their harvest (increase smolt release), they will find that they are overharvesting their stocks relative to the new level of total smolt release. In the long-run, competition in the ocean from smolts released tc the ocean by competitors will reduce the original salmon ranchers' share of total returning adult salmon to zero.

(B) Profit Maximizing Salmon Rancher: No Natural Fishery.

The profit maximizing problem of the salmon rancher can be formulated by equations:

$$\max_{H_t} \sum_{t=1}^{\infty} \alpha^{t-1} R(H_t,W_t) = \max_{H_t} \sum_{t=1}^{\infty} \alpha^{t-1}[(p-c_1)H_t W_t - c_2(W_t - H_t W_t)] \qquad (1.8)$$

subject to

$$W_{t+1} - W_t = \frac{W_t - H_t W_t}{a+b(W_t - H_t W_t)} - W_t = g(H_t W_t) - W_t \tag{1.9}$$

and appropriate nonnegativity and terminal conditions. The discount factor is α^{t-1}, where $\alpha = \frac{1}{1+r}$ with r denoting the periodic discount rate.

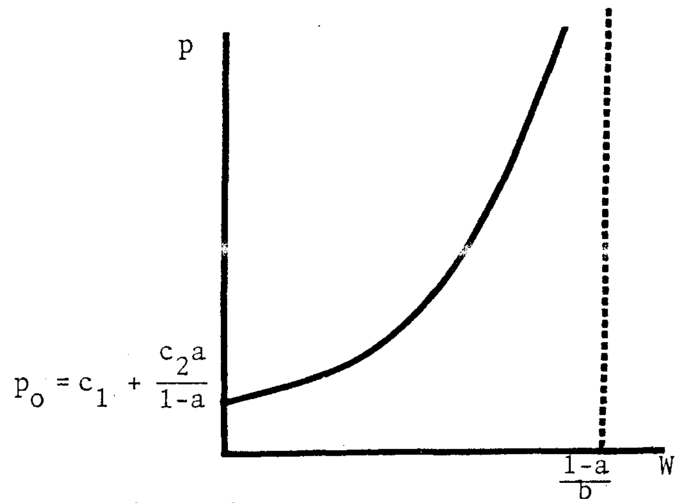

Figure 1a. Competitive Equilibrium Aquaculture Recruitment

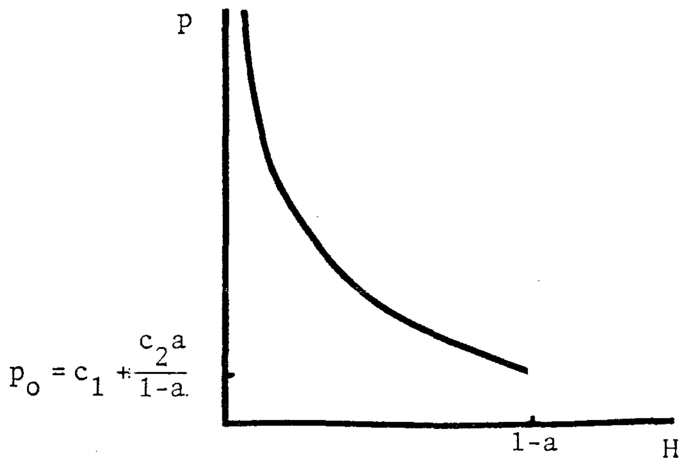

Figure 1b. Competitive Equilibrium Aquaculture Harvest Rate

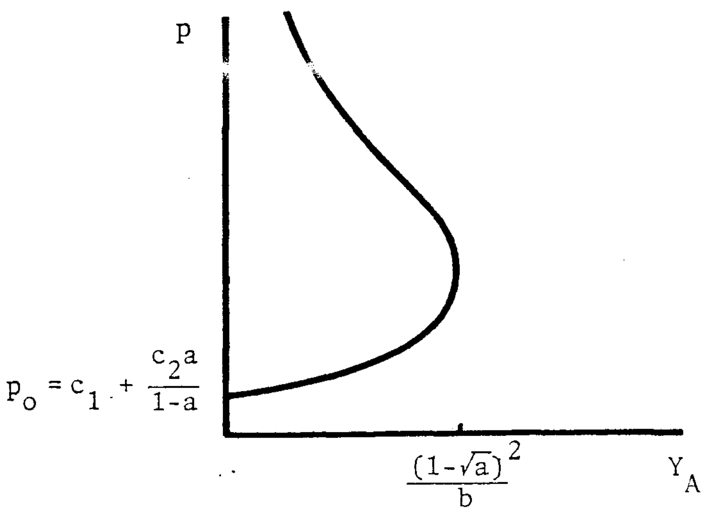

Figure 1c. Competitive Equilibrium Aquaculture Supply.

The Hamiltonian is

$$H = \alpha^{t-1}[(p-c_1)H_tW_t - c_2(W_t - H_tW_t) + \lambda_t[\frac{W_t - H_tW_t}{a+b(W_t-H_tW_t)} - W_t] \qquad (1.10)$$

The first order conditions are:

$$\frac{\partial H}{\partial W} = \alpha^{t-1}[(p-c_1)H_t - c_2(1-H_t)] + \lambda_t[\frac{a(1-H_t)}{(a+b(W_t-H_tW_t))^2} - 1] \qquad (1.11)$$

$$= -(\lambda_t - \lambda_{t-1})$$

$$\frac{\partial H}{\partial H} = \alpha^{t-1}[(p-c_1+c_2)W_t] - \lambda_t\frac{aW_t}{(a+b(W_t-H_tW_t))^2} \qquad (1.12)$$

$$\frac{\partial H}{\partial \lambda} = W_{t+1} - W_t \qquad (1.13)$$

In equilibrium

$$\lambda_t = \alpha^{t-1}\frac{(p-c_1+c_2)(a+b(W_t-H_tW_t))^2}{a} \qquad (1.14)$$

and

$$\lambda_t - \lambda_{t-1} = (\alpha^{t-1} - \alpha^{t-2})\frac{(p-c_1+c_2)(a+b(W_t-H_tW_t))^2}{a} \qquad (1.15)$$

Substituting (1.14), (1.15) and the equilibrium values for W derived from 1.9 into 1.12 results in the equilibrium condition

$$\alpha^{-1} = 1+r = \frac{a(p-c_1)}{(p-c_1+c_2)(1-H^*)^2} \qquad (1.16)$$

Condition 1.16 can easily be derived in general terms and is given by

$$\alpha^{-1} = 1 + r = g'_W - \frac{R'_W g'_H}{R'_H} \qquad (1.16a)$$

This condition implies that the optimally managed salmon ranch should select a recruitment level W and corresponding harvest rate H such that the marginal impact of current recruitment on net future recruitment (g'_W-1) minus the ratio of marginal net revenue from recruitment divided by marginal net revenue of the harvest rate times marginal impact of the harvest rate on future recruitments equals the discount rate, r.

Solving for the equilibrium harvest rate, H*, from (1.16)

$$H^* = 1 - \frac{\sqrt{\alpha a(p-c)}}{\sqrt{p-c_1+c_2}} \tag{1.17}$$

Then W* and Y_A^* are

$$W^* = \frac{1}{b} - \frac{\sqrt{a(p-c_1+c_2)}}{b\sqrt{\alpha(p-c_1)}} \tag{1.18}$$

$$W^*H^* = Y_A^* = \left[1 - \frac{\sqrt{\alpha a(p-c_1)}}{\sqrt{p-c_1+c_2}}\right]\left[\frac{1}{b} - \frac{\sqrt{a(p-c_1+c_2)}}{b\sqrt{\alpha(p-c_1)}}\right] . \tag{1.19}$$

The equilibrium curves for W*, H* and Y_A^* are illustrated in Figure 2a,b,c. In contrast to the open access ocean ranching situation, the equilibrium supply for the profit maximizing salmon rancher is always increasing with price and decreasing with the interest rate. This results directly from the fact that the common property externality of open access is eliminated and the profit maximizer takes into account the discount rate so that over-stocking of salmon smolts will not occur. The profit maximizer will supply at maximum sustainable yield levels as price approaches infinity and as the discount rate goes to zero (α approaches 1). Note that the salmon rancher will not produce if $\alpha > 1$ which, of course, could only occur if the discount rate were negative.

2. Ocean Ranchers and Fishermen

(A) Open Access

An analysis of the open access fishery/aquaculture industry without interspecific interaction can be done by evaluating the following modified profit and population equations:

$$\text{Fishery profit} = \pi_F = [p(X_t+W_t)-c]E_t \tag{2.1}$$

$$\text{Aquaculture profit} = \pi_A = [(p-c_1)H_tW_t-c_2(W_t-H_tW_t-E_tW_t)] \tag{2.2}$$

$$\text{Natural stock dynamics} = X_{t+1} = \frac{X_t-E_tX_t}{a'+b'(X_t-E_tX_t)} \tag{2.3}$$

$$\text{Aquaculture stock dynamics} = W_{t+1} = \frac{W_t-H_tW_t-E_tW_t}{a+b(W_t-H_tW_t-E_tW_t)} \tag{2.4}$$

where X_t is the recruitment of natural adult salmon in t

E_t is the fishing effort in t, and

c is cost per unit effort (assumed constant).

The key addition is the fact that the fishermen may harvest both the natural and aquacultured fish but cannot discriminate between them. The aquaculturalist, however, cannot harvest the natural stock. This is because it is assumed that the homing instinct of the aquacultured fish is accurate enough so that they end up back at the aquaculture facility while the natural

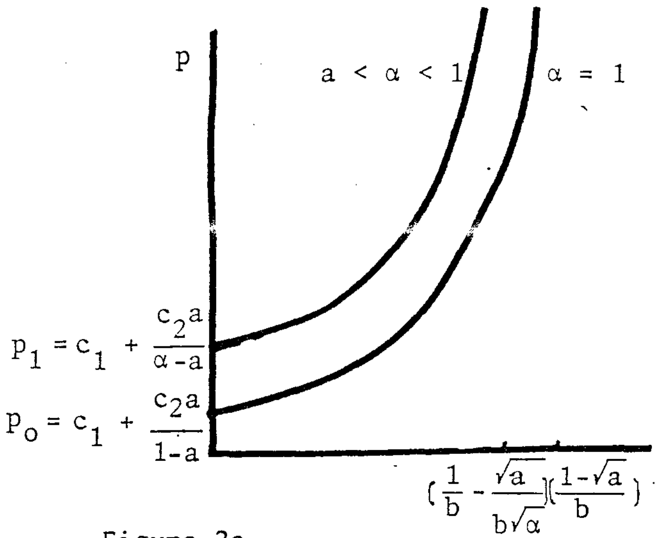

Figure 2a. Profit Maximizing Equilibrium Aquaculture Recruitment

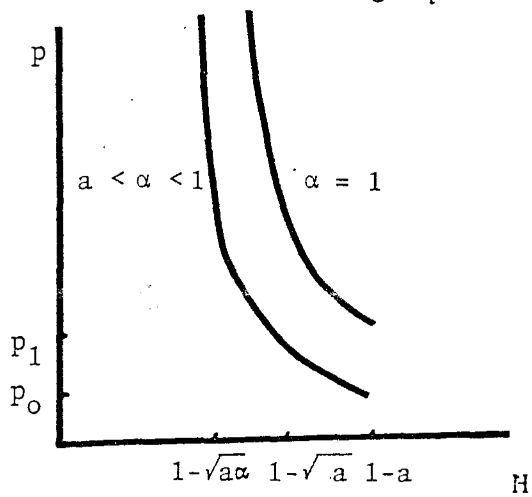

Figure 2b. Profit Maximizing Equilibrium Aquaculture Harvest Rate

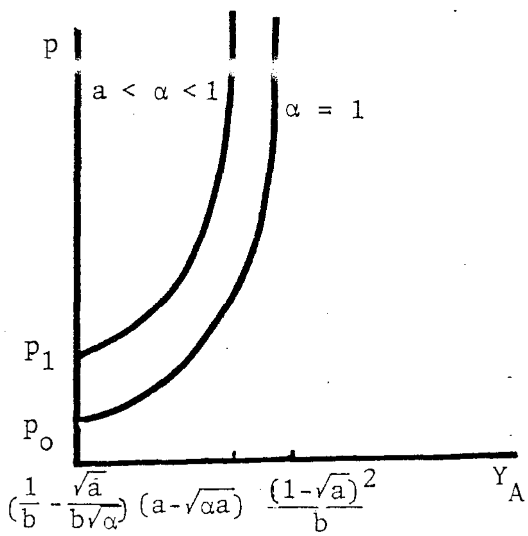

Figure 2c. Profit Maximizing Equilibrium Aquaculture Supply

stock head to their native tributaries. It is further assumed that the salmon rancher does not participate in conventional fishing. The cost function for aquaculture is modified through the impact of fishing effort on the returning adult salmon. The greater the fishing effort, the fewer fish will return to the aquaculture facility, thus reducing total aquaculture expense.

In this paper, it is assumed that the survival rate of aquacultured salmon smolts is greater than or equal to the survival rate of the natural salmon stocks because the egg to smolt mortality is reduced. This implies that $a \leq a'$ and $b \geq b'$.

In an open access equilibrium, the profits to both sectors must be zero and the population must be in steady state, so that $X_{t+1} = X_t$ and $W_{t+1} = W_t$ where $0 \leq X \leq \frac{1-a'}{b'}$ and $0 \leq W \leq \frac{1-a}{b}$.

From equation (2.1), the zero profit condition for fishing implies

$$X + W = \frac{c}{p} \text{ or } X = \frac{c}{p} - W. \qquad (2.5)$$

Solving (2.3) for E, substituting into (2.4), solving for H, then substituting the expression for E and H into (2.2) gives

$$W = \frac{1}{b} + (bX-1)\,\frac{a(p-c_1+c_2)}{ba'(p-c_1)}. \qquad (2.6)$$

Condition (2.5) is the zero profit requirement for the fishery and condition (2.6) captures the zero profit and population equilibrium requirements for the salmon rancher. Figure 3 shows these conditions in the (X,W) plane. Since $a \geq a'$ and $b \geq b'$, the intercept of W defined by (2.6) is always less than $\frac{1-a}{b}$, and the coefficient on X is always less than one and positive.

The intersection of the two conditions (2.5) and (2.6) in the positive quadrant results in a system equilibrium where both stocks of fish survive.

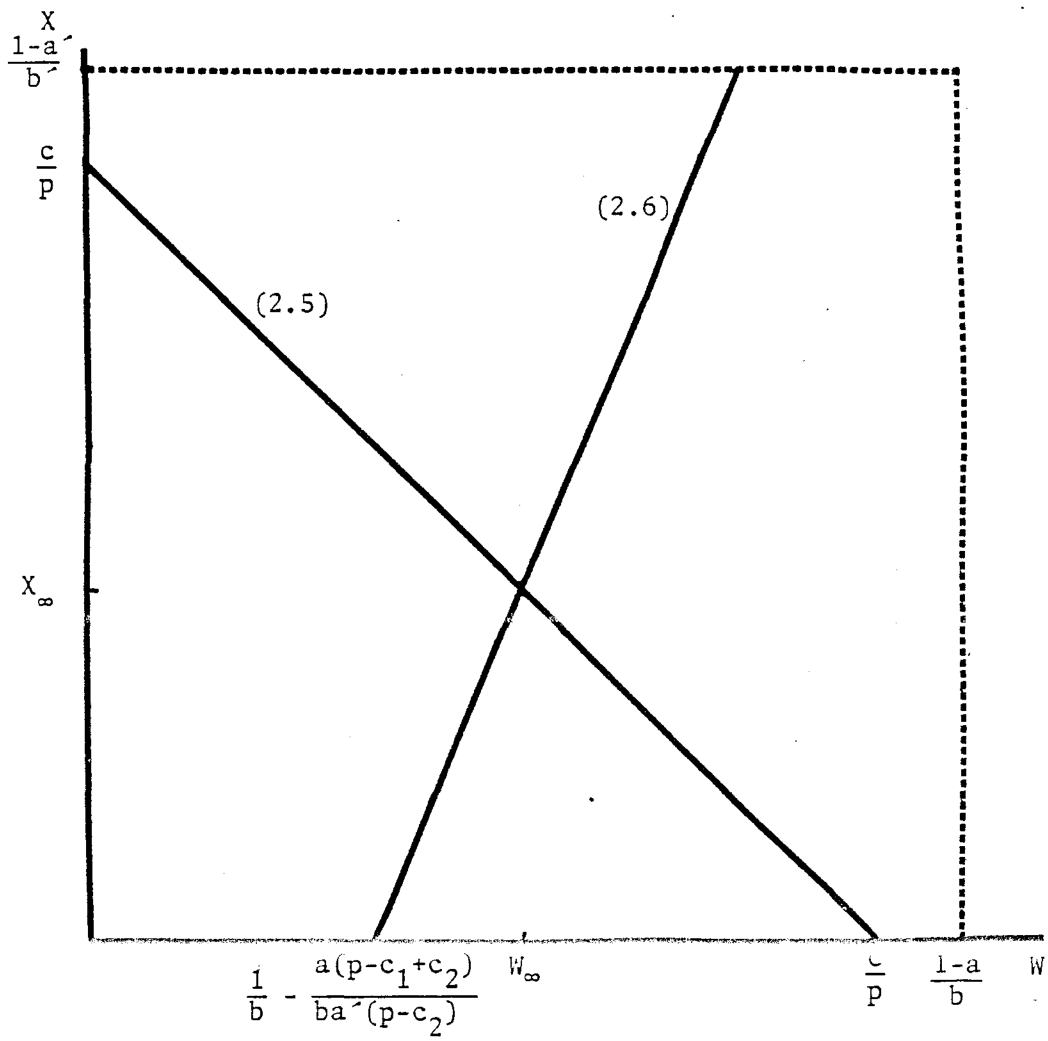

Figure 3. Competitive Equilibrium Aquacultural and Natural Fish Recruitment

If the W-axis intercept, defined by (2.6), exceeds that defined by (2.5), the natural fish stock is eliminated in equilibrium. This occurs when

$$\frac{1}{b} - \frac{a(p-c_1+c_2)}{a'b(p-c_1)} > \frac{c}{p} . \tag{2.7}$$

If the line in (2.6) intersects the X-axis above c/p, the aquaculturalists will not produce so there are no aquacultured fish at equilibrium.

In the one species model, a population can never be completely eliminated by overfishing because, as X goes to zero, the cost of unit harvesting goes to infinity. However, when two populations are exploited simultaneously, one population may be driven to extinction while the remaining population supports the system in bionomic (one-species) equilibrium [7]. Although it is possible to eliminate the natural stock of fish, it is impossible for the aquaculturalist to eliminate competition from natural fishermen in the open access model.

(B) Open Access Equilibrium Supply

The supply from aquaculture and the fishery will have three distinct regions along the price axis. Initially, at low prices, all supplied salmon will come from fishermen exploiting natural recruitment. As demand increases the aquaculturalist will enter and the supply of fish will come from fishermen fishing natural and aquacultural fish as well as from aquaculturalists. Finally, as demand increases further and equilibrium price continues to rise, the fishing effort on the natural stock will become excessive, eliminating the natural fish and resulting in a supply derived only from aquacultured fish.

When the salmon ranchers are not present, the demand depends only on the natural fishery. The supply in price-quantity space for this case is illustrated in Figure 4 and labeled $Y_{T|X}$ (supply given only natural fish).

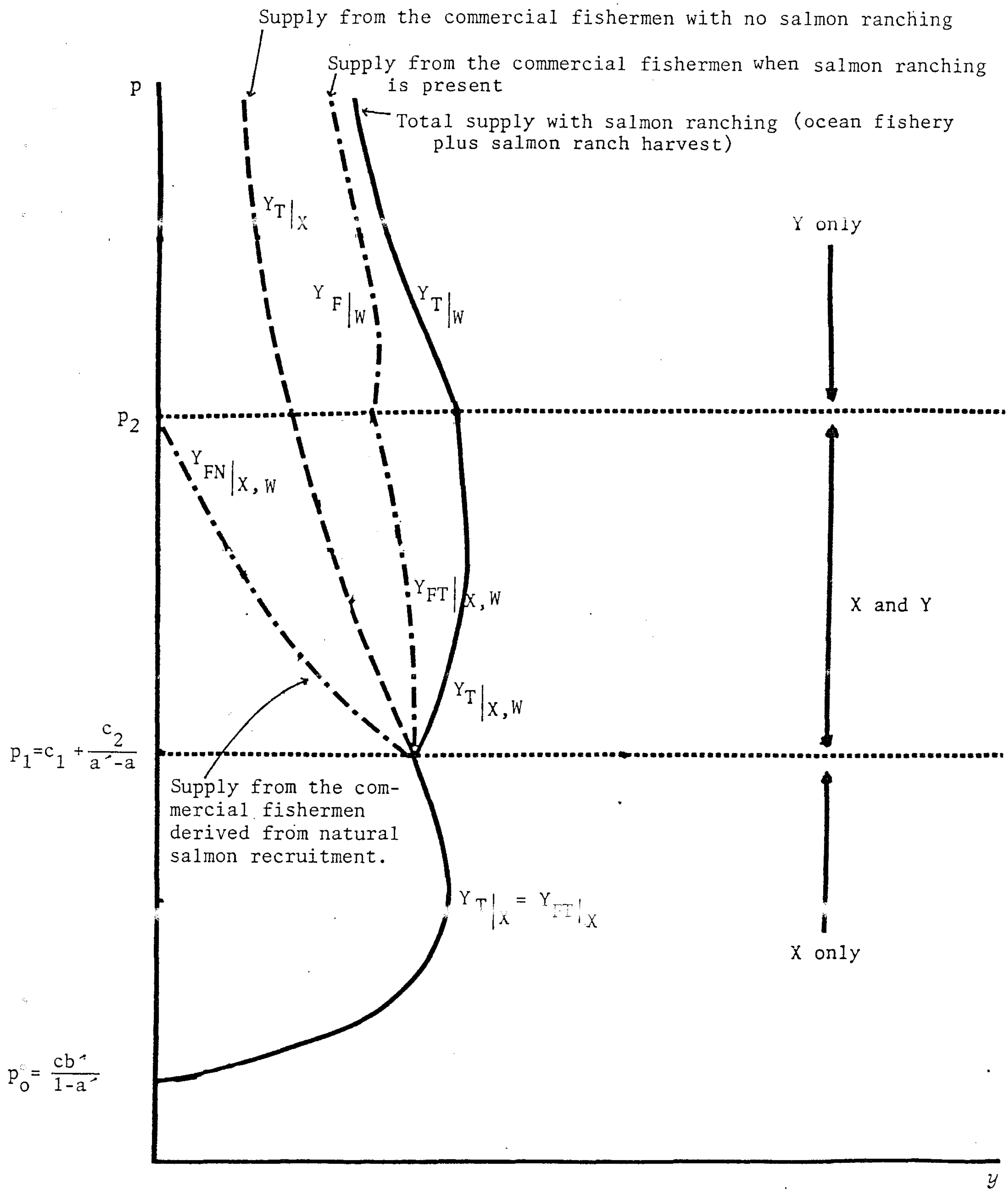

Figure 4. Competitive Equilibrium Supply

The supply with both fish stocks is relatively straightforward to compute from equilibrium equations conditions (2.5) and (2.6) and

$$E = \frac{a'}{b'X-1} + 1 \tag{2.8}$$

$$H = \frac{a}{bW-1} - \frac{a'}{b'X-1} . \tag{2.9}$$

The supply curves derived from these equations were generated numerically and appear in Figure 4 labeled $Y_{T|XW}$, $Y_{FN|X,W}$ and $Y_{FA|XW}$ (total supply, fishery supply from natural stock and fishery supply from aquacultural stock, respectively). In this range, total equilibrium supply from aquacultured and natural fish is $Y_{T|XW}$ = EX + EW + HW. The equilibrium supply from the fishery is $Y_{FT|XW}$ = EX + EW. The salmon ranchers' equilibrium supply is $Y_{A|XW}$ = $Y_{T|XW} - Y_{TF|XW}$ = HW.

When the conditions necessary for both species to coexist are exceeded, only the aquacultured fish will be left. The zero profit condition for the fishery is π_F = (pW-c)E which implies $W = \frac{c}{p}$. Making the appropriate substitutions results in

$$H = \frac{c_2 pa}{(p-c_1+c_2)(p-bc)} \tag{2.10}$$

and

$$E = a - \frac{pa}{p-bc} [1 + \frac{c_2}{p-c_1+c_2}] \tag{2.11}$$

The resulting supply from the fishery is

$$Y_F = EW = \frac{c}{p} - \frac{a}{p-bc} - \frac{c\ c_2 a}{(p-c_1+c_2)(p-bc)} \tag{2.12}$$

and from the aquaculturist is

$$Y_A = HW = \frac{c\ c_2 a}{(p-c_1+c_2)(p-bc)} \tag{2.13}$$

and total supply is

$$Y_T = EW + HW = \frac{c}{p} - \frac{a}{p-bc} \tag{2.14}$$

Referring to Figure 4, the supply equations when only aquacultured stock exist are labeled $Y_{F|W}$ and $Y_{T|W}$ (supply from fishery, total supply, respectively). The aquaculturalist supply is $Y_{T|W} - Y_{F|W} = Y_{A|W}$. In Figure 4, at prices below $p_o = \frac{cb'}{1-a'}$, there is no supply. When the equilibrium price ranges from p_o to $p_1 = c_1 + \frac{c_2}{a'-a}$, the supply comes from the open access fishery exclusively. As price rises above p_1, the aquaculturalists will enter.

As demand increases further to p_2, fishing effort becomes so great that the equilibrium natural fish stock becomes zero. At prices above p_2 the supply is composed on only aquacultured fish caught by fishermen and aquacultured fish supplied by the ocean ranchers. The curve label $Y_{T|X}$ represents the supply if salmon ranching is not present.. Note that supply is less at all prices than when aquaculture is not present.

It has been observed in Clark [7] that the backward bending open-access fishery supply, $Y_{T|X}$, and a downward sloping demand may result in multiple equilibria. The entry of fish ranching shifts total supply, Y_T, to the right and reduces this backward bending characteristic. Correspondingly, the range of conditions where multiple equilibria can occur is reduced implying increased stability.

Figures 5a,b,c show the equilibrium aquaculture stock, aquaculturalist harvest rate and fishing effort rate as price increases. Fishing effort in

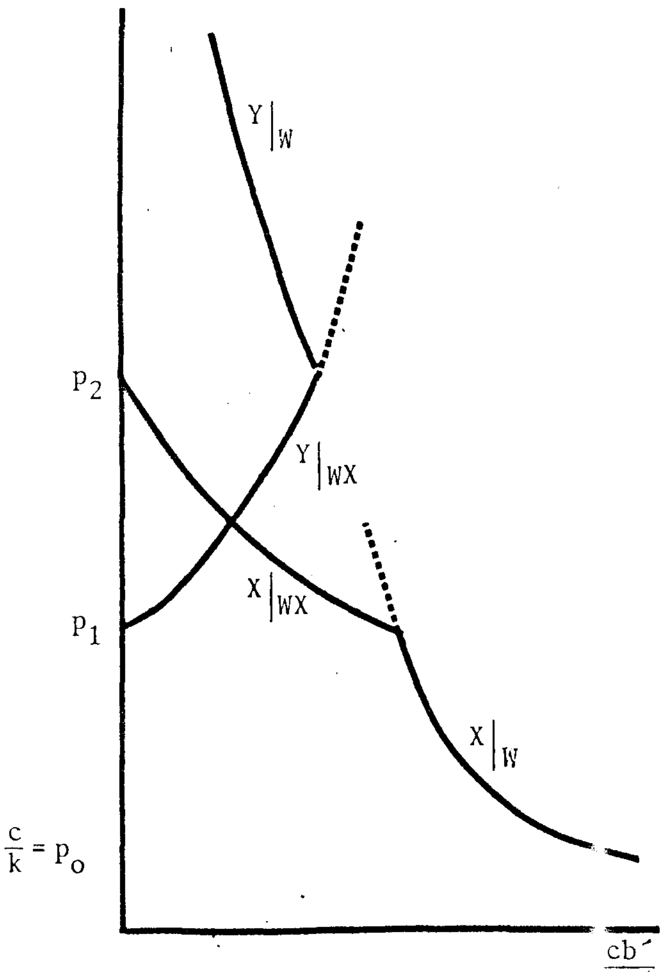

Figure 5 a Equilibrium fish Recruitment

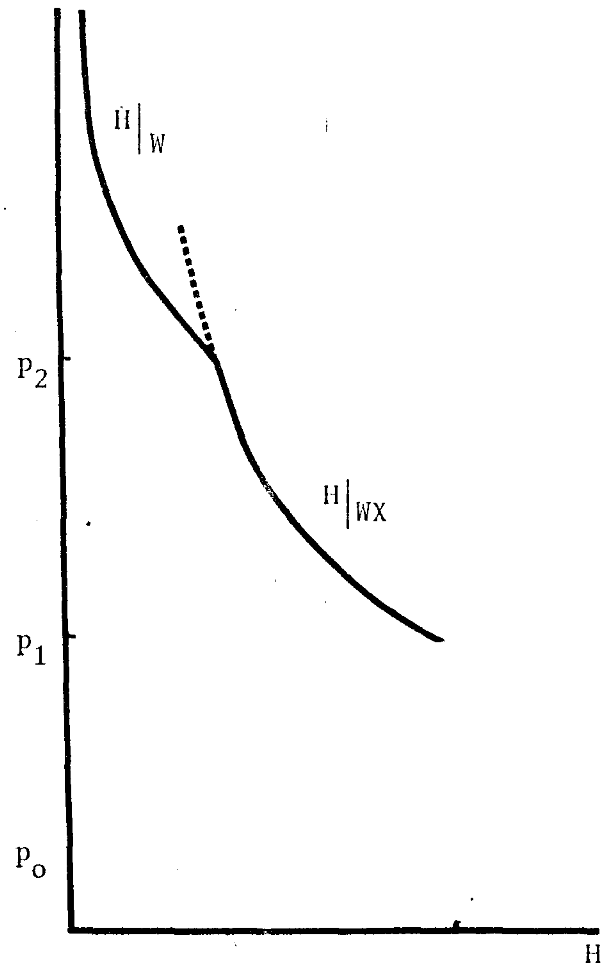

Figure 5 b Equilibrium Aquaculturalist Harvest Rate

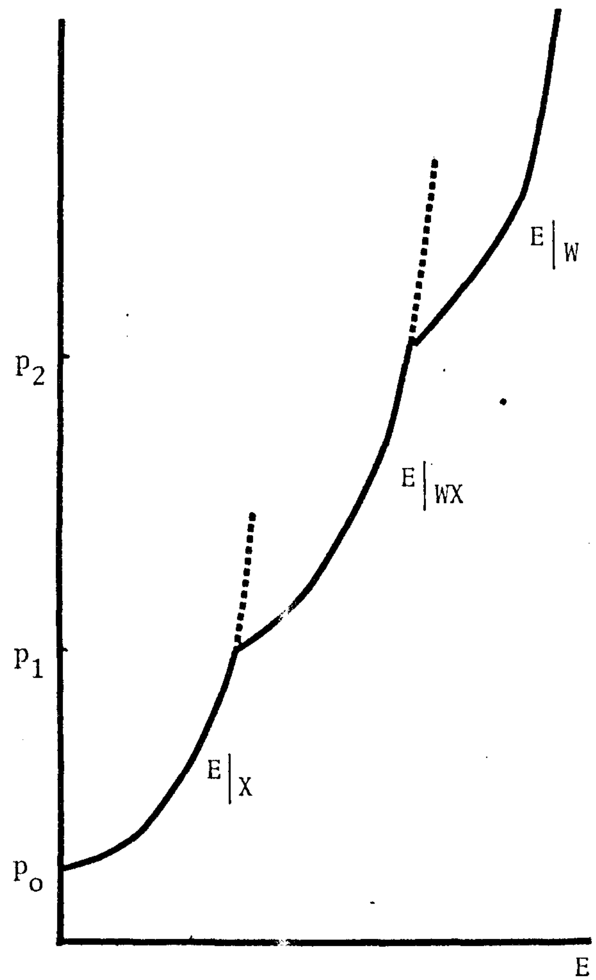

Figure 5c Equilibrium Fishing Effort

Figure 5c is steadily increasing with price. The entry of the salmon ranchers causes fishing effort to shift to the right relative to the natural fish only case. When the natural fish stock is eliminated, the fishing effort shifts even further than in the previous situations for similar prices. The aquaculture recruitment increases while both stocks are maintained and aquacultured harvest steadily decreases as in the open access aquaculture case described earlier. When the natural stock is eliminated, the harvest rate by salmon ranchers continues to decrease but at a faster rate. This is caused by the effect of additional fishery effort on the return of aquacultured fish. Since an open access fishery will always fish such that the total recruitment is equal to $\frac{c}{p}$, the recruitment must asymptotically approach zero as price approaches infinity. No matter how much the salmon ranchers produce (i.e. reduce harvest rate), recruitment will decline once the natural fish stock is eliminated. This contrasts with the open access aquaculturalist case with no competition from the fishery where the aquacultured recruitment approaches the replacement parent stock $\frac{1-a}{b}$.

Finally, consider the case where demand decreases after the natural stock has become extinct. Obviously, as equilibrium decreases below p_2, it can not move back along the $Y_{T|XW}$ in Figure 6. The equilibrium must be on the $Y_{T|W}$ curve as in Figure 6. If the wild stock does not recover, and the price drops below equilibrium price p_3, the aquaculturalist will shut down until price recovers. Equilibria below point a require negative equilibrium harvest by the fishermen which is impossible. Therefore, the lower bound for a viable salmon ranching operation is higher than when the wild stock existed. If a wild stock is maintained, the range of prices under which both fishermen and aquaculturists remain productive is increased.

Figure 5c is steadily increasing with price. The entry of the salmon ranchers causes fishing effort to shift to the right relative to the natural fish only case. When the natural fish stock is eliminated, the fishing effort shifts even further than in the previous situations for similar prices. The aquaculture recruitment increases while both stocks are maintained and aquacultured harvest steadily decreases as in the open access aquaculture case described earlier. When the natural stock is eliminated, the harvest rate by salmon ranchers continues to decrease but at a faster rate. This is caused by the effect of additional fishery effort on the return of aquacultured fish. Since an open access fishery will always fish such that the total recruitment is equal to $\frac{c}{p}$, the recruitment must asymptotically approach zero as price approaches infinity. No matter how much the salmon ranchers produce (i.e. reduce harvest rate), recruitment will decline once the natural fish stock is eliminated. This contrasts with the open access aquaculturalist case with no competition from the fishery where the aquacultured recruitment approaches the replacement parent stock $\frac{1-a}{b}$.

Finally, consider the case where demand decreases after the natural stock has become extinct. Obviously, as equilibrium decreases below p_2, it can not move back along the $Y_{T|XW}$ in Figure 6. The equilibrium must be on the $Y_{T|W}$ curve as in Figure 6. If the wild stock does not recover, and the price drops below equilibrium price p_3, the aquaculturalist will shut down until price recovers. Equilibria below point a require negative equilibrium harvest by the fishermen which is impossible. Therefore, the lower bound for a viable salmon ranching operation is higher than when the wild stock existed. If a wild stock is maintained, the range of prices under which both fishermen and aquaculturists remain productive is increased.

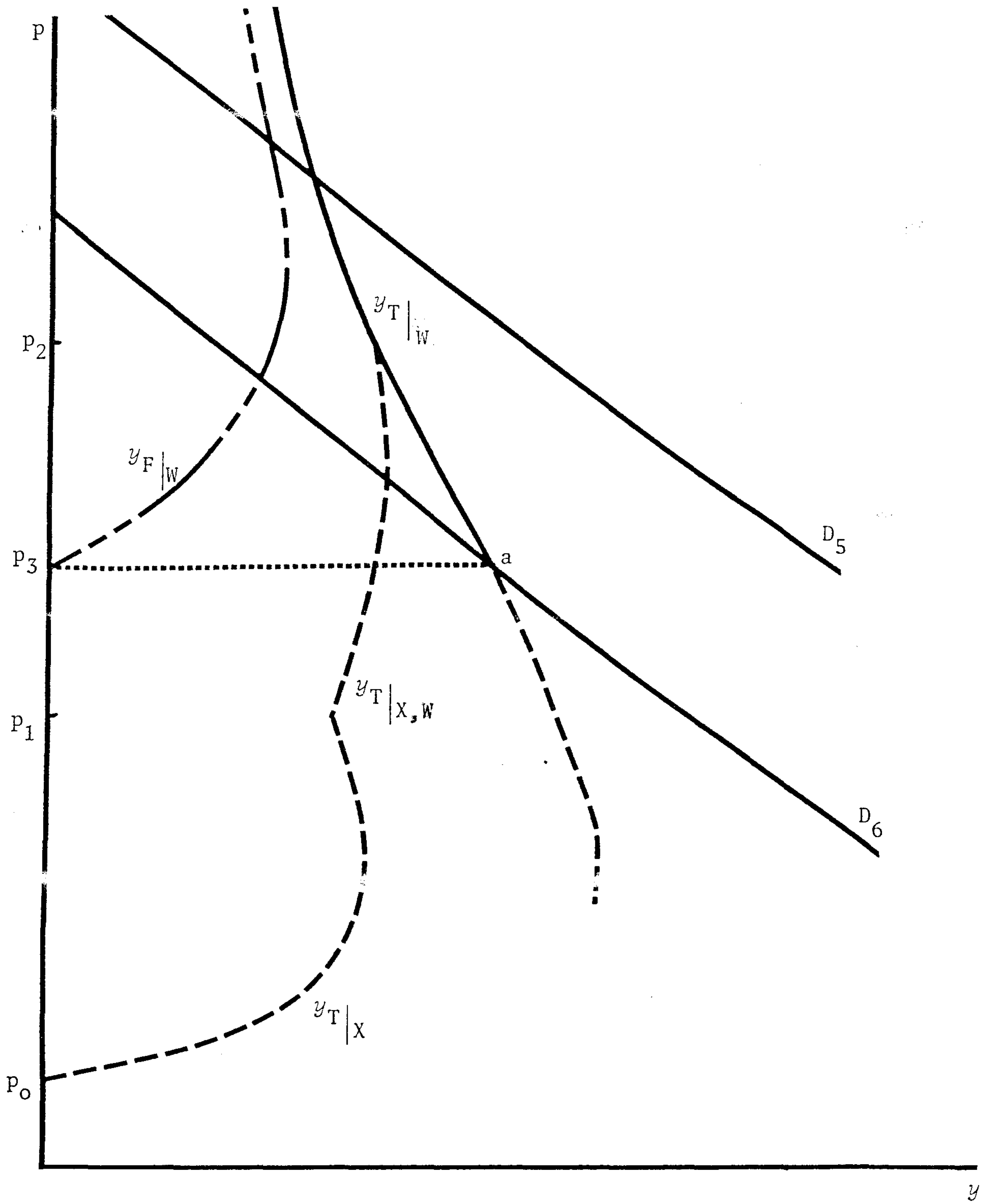

Figure 6. Equilibrium Supply After Natural Fish Stock Elimination

3. Evaluation of Selected Constraints on the Commercial Fishery

(A) Catchability of the Aquacultured Fish is Less than for Natural Fish

Regulations could be enacted which would reduce the ability of the fishermen to catch the aquacultured fish stock relative to natural stock. This could happen, for example, if it were made illegal to fish within some radius of the aquaculture facility. Catchability of aquacultured fish could also be reduced through timing of smolt release, resulting in returns which are somewhat out of phase with the fishing season or by encouraging the return of younger fish. The addition of reduced catchability to the model would result in the modification of equations (2.1), (2.2) and (2.4); (2.3) would remain the same.

$$\pi_F = [p(X_t + \delta W_t) - c]E_t \tag{3.1}$$

$$\pi_A = (p-c_1)H_t W_t - c_2(W_t - H_t W_t - \delta E_t W_t) \tag{3.2}$$

$$W_{t+1} = \frac{W_t - H_t W_t - \delta E_t W_t}{a + b(W_t - H_t W_t - \delta E_t W_t)} \tag{3.3}$$

where $\delta < 1$.

Solving for the equilibrium, open access condition as before results in the following conditions analogous to (2.5) and (2.6).

$$\frac{c}{p} = \delta W + X \tag{3.4}$$

$$W = \frac{1}{b} + (b'X-1)\,\frac{a(p-c_1+c_2)}{b(p-c_2)(\delta a' - (b'X-1)(1-\delta))} \tag{3.5}$$

An illustration of (2.5) and (2.6) compared to (3.4) and (3.5) is in Figure 7. Notice that condition (3.4) has a larger W intercept and smaller slope than (2.5) since $\frac{c}{p} < \frac{c}{p\delta}$. Also, the W, given by condition (3.5), is

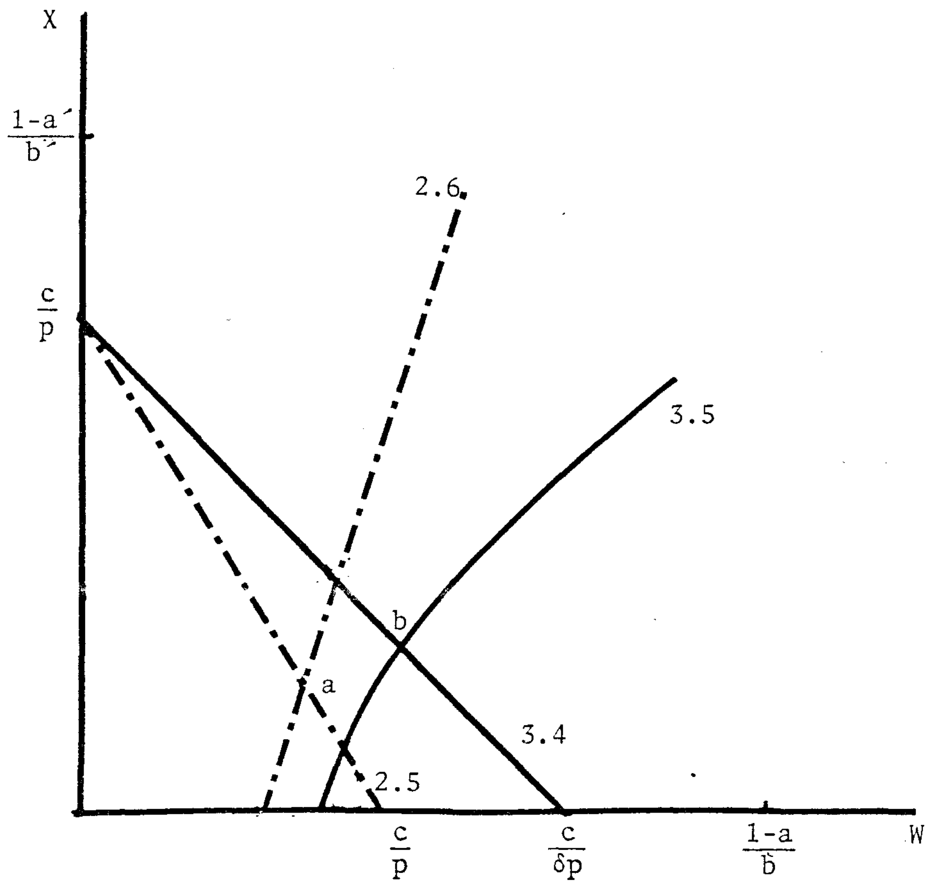

Figure 7. Competitive Equilibrium Recruitment with Reduced Aquaculture Stock Catchability

everywhere greater than the W given by condition (2.6) in the positive orthant because $a' < 1-b'X$, therefore $\delta a'-(b'x-1)(1-\delta) > a'$ which decreases the last term in (3.5). It is indeterminant whether the equilibrium X (point b) will be greater than the first case but for all $\delta < 1$ the equilibrium aquacultured salmon recruitment will increase.

(B) Fishing Effort is Constrained

In this case, at some natural fish stock level, a management agency requires that fishing effort, E, cannot exceed $\bar{E}$ to prevent the extinction of the natural stock. The supply relationship is easily attained. When $\bar{E}$ is not binding, the supply is the same as in the original open access problem. At some equilibrium price, p_1, $\bar{E}$ becomes binding. Above price p_1 the natural stock of fish remains constant at $\bar{X}$ and the supply from the natural fishery remains constant at $\bar{E}\bar{X} = \bar{Y}_F$. It is then straightforward to solve for the equilibrium open access salmon ranchers' recruitment and harvest rate. The supply relationships and the supply if only the natural fishery exists are shown in Figure 8. Notice that the price at which the restriction on effort is imposed, p_1, is higher when there is no aquaculture than the limit price, p_1, with salmon ranchers present. The fishery is more exploitive of the natural stock when the salmon ranchers are present, so the restriction on effort would tend to be needed at lower prices.

When fishing effort is restricted, the aquaculture stock will continue to increase as price goes up. This is similar to the open access case with no fishery competition discussed earlier.

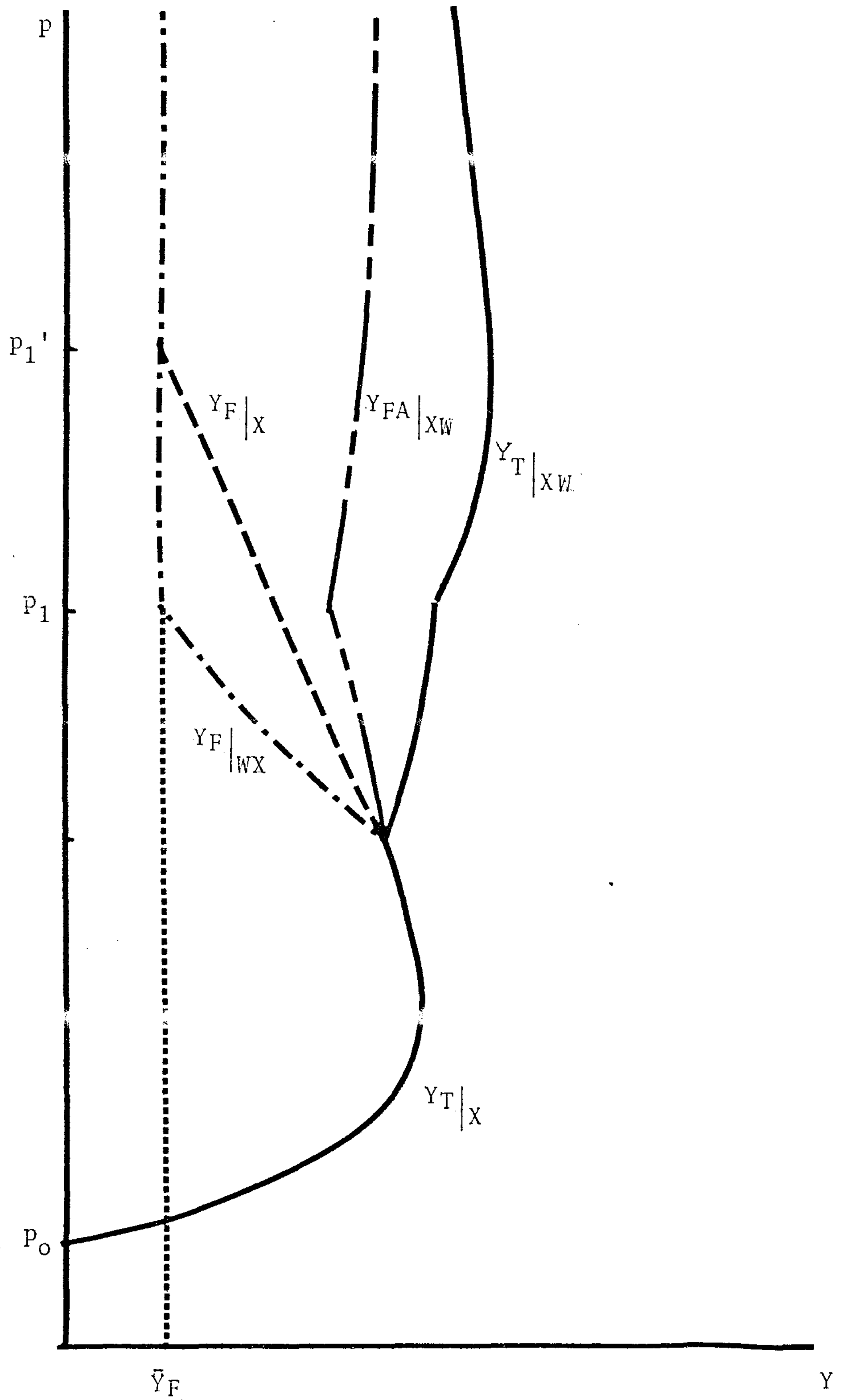

Figure 8. Equilibrium Supply with a Maximum Fishing Effort Constraint

4. Profit Maximizing Salmon Ranchers and an Open Access Fishery

Under current conditions, the vast majority of salmon ranching in Oregon is done by one firm. Therefore, it is useful to consider the case where the salmon rancher acts as a profit maximizer facing competition from the open access commercial fishery. The analogous situation can also result from the fact that salmon ranching is restricted by several regulatory practices and the limited number of suitable sites. In this model, it is assumed that the productivity of any individual salmon rancher is small enough so that he remains a price taker in the overall market. However, it is also assumed that the aquaculturalists can have a significant impact on the regional salmon catch. In the case studied here, the salmon rancher exerts power to control his profits through the limit in site availability and through his influence on regional salmon catch. The problem from the salmon rancher's point of view is to maximize profit given that he faces an open access fishery. That is

$$\max \pi = \sum_{t-1}^{\infty} \alpha^{t-1}[(p-c_1)H_tW_t - c_2(W_t - H_tW_t - E_tW_t)] \tag{4.1}$$

Subject to

$$W_{t+1} - W_t = \frac{W_t - H_tW_t - E_tW_t}{a+b(W_t - H_tW_t - W_tW_t)} - W_t \tag{4.2}$$

$$X_{t+1} - X_t = \frac{X_t - E_tX_t}{a'+b'(X_t - E_tW_t)} - X_t \tag{4.3}$$

$$E_{t+1} - E_t = \gamma E_t(p(X_t + W_t) - c) - E_t \tag{4.4}$$

$$H_t, E_t, X_t, W_t \geq 0.$$

Solving for the optimal stationary recruitment and harvest given E results in

$$W^* = \frac{1}{b} - \frac{\sqrt{a(p-c_1+c_2)}}{b\sqrt{\alpha(p-c_1)(1-E)}} \tag{4.5}$$

$$H^* = 1 - E - \frac{\sqrt{\alpha a(p-c_1)(1-E)}}{\sqrt{p-c_1+c_2}} \tag{4.6}$$

In equilibrium, the zero profit fishery has a fishing effort and natural recruitment of

$$E^{\circ} = 1 - \frac{a'}{1-b'X^{\circ}} \tag{4.7}$$

and

$$X^{\circ} = \frac{c}{p} - W^{*} \tag{4.8}$$

If E° is substituted for E in equation (4.5), the result is

$$W^{*} = \frac{1}{b} - \frac{\sqrt{a(p-c_1+c_2)(1-b'x)}}{b\sqrt{\alpha a'}(p-c_1)} \ . \tag{4.9}$$

The two equilibrium conditions (4.8) and (4.9) are graphed in Figure 9. The condition for elimination of the natural salmon stock is now

$$\frac{1}{b} - \frac{\sqrt{a(p-c_1+c_2)}}{b\sqrt{\alpha a'}(p-c_1)} > \frac{c}{p} \tag{4.10}$$

Comparing (4.10) with the analogous condition (2.7) when both fishery and aquaculture are open access, it can be seen that the price at which the natural fish stock is eliminated is higher in this case.

The supply equations for the open access common property fishery and for profit maximizing salmon ranching were numerically calculated. The general shape of the supply curve is the same as presented in Figure 4. From prices $p_o = \frac{cb'}{1-a'}$ to $p_1 = c_1 + \frac{c_2}{\sqrt{\alpha a'}-\sqrt{a}}$, the fish supply is derived from the natural fishery only. In the open access case previously discussed, the aquaculturist enters at a lower price. Above p_1, the ocean rancher enters, continually increasing his harvest and the aquacultured stock until p_2 is reached. At prices above p_2, the natural stock is eliminated and the remaining supply is aquacultured fish caught by the fishermen or harvested by the aquaculturaist. The supply decreases as price rises above p_2. As the fishermen increase

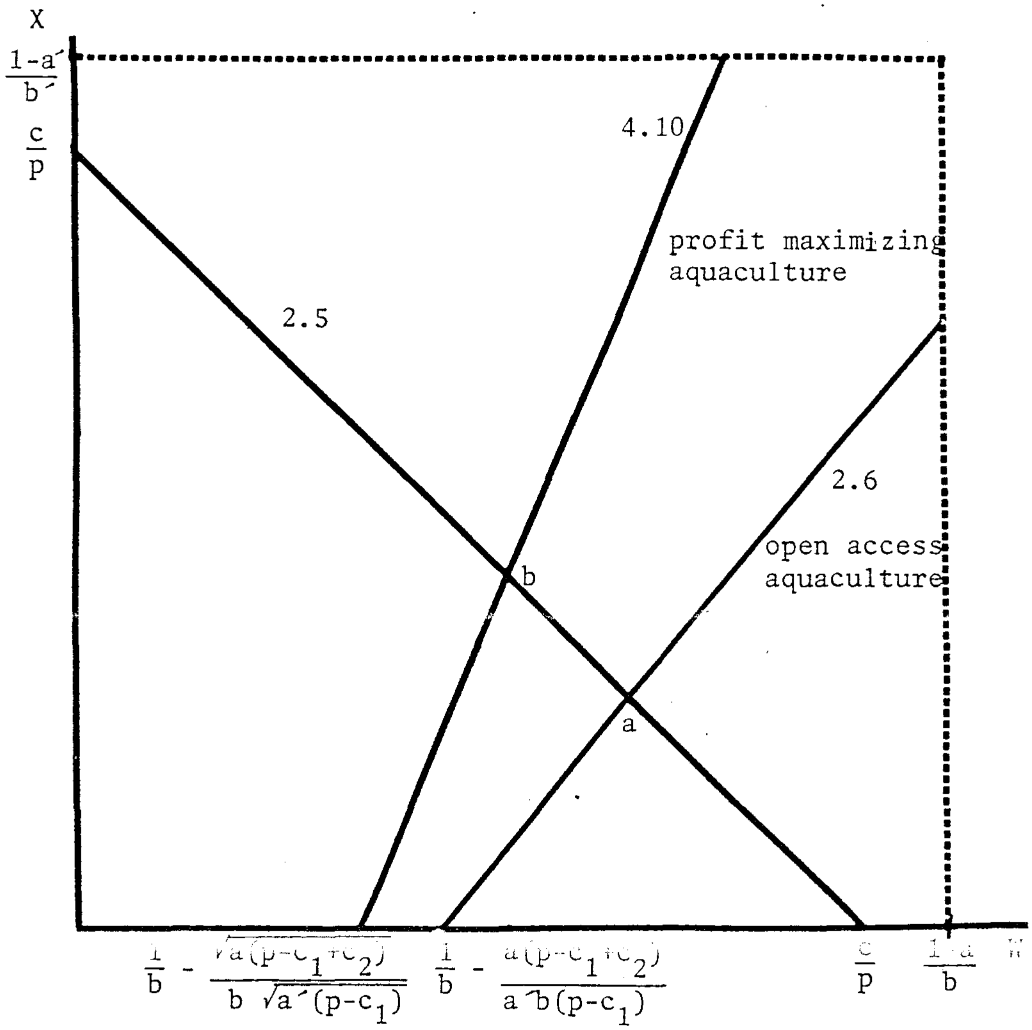

Figure 9. Maximum Aquaculture Profit Equilibrium Recruitment vs. Open Access Aquaculture Equilibrium Recruitment

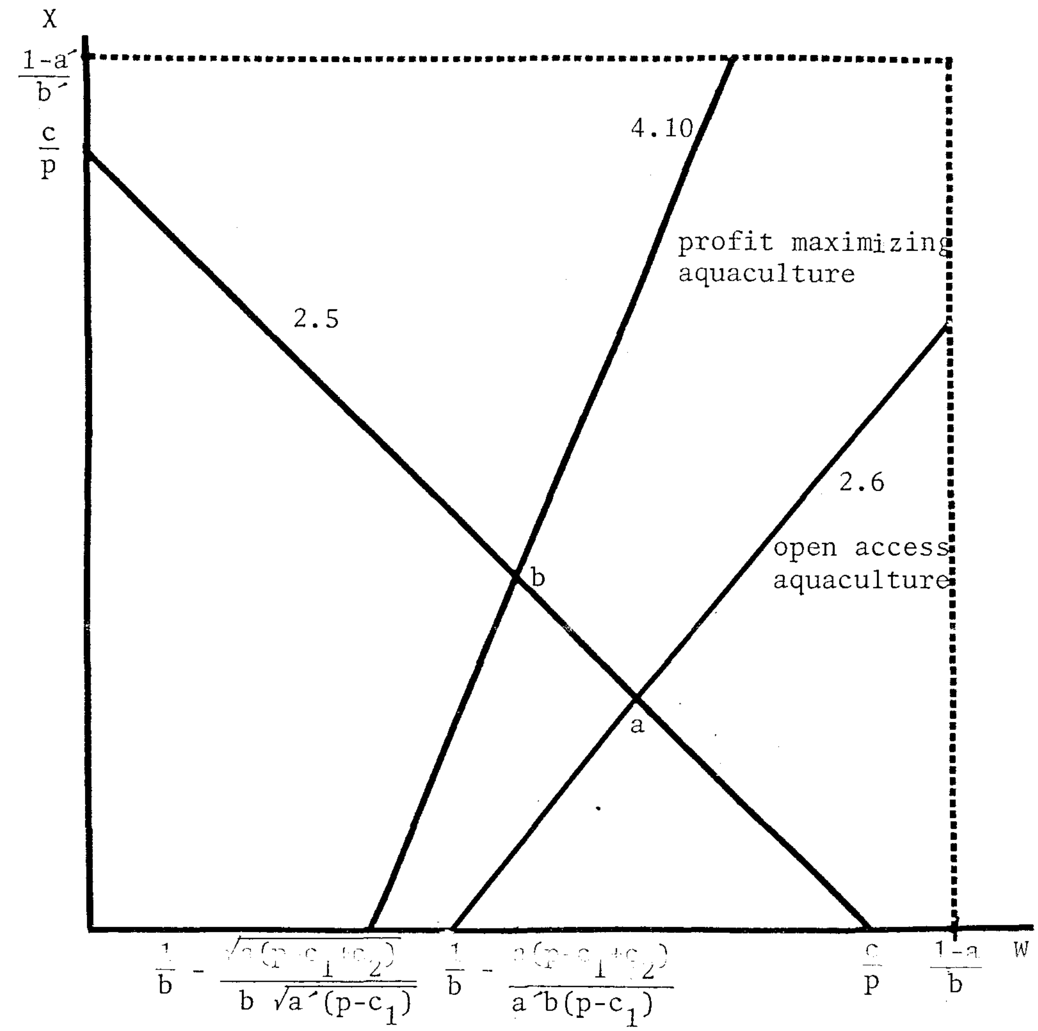

Figure 9. Maximum Aquaculture Profit Equilibrium Recruitment vs. Open Access Aquaculture Equilibrium Recruitment

effort rate, the salmon rancher also decreases harvest rate to maximize profit driving down the aquaculture stock such that $W = \frac{c}{p}$. The price determines stock level at $\frac{c}{p}$ and the salmon rancher determines the distribution of the harvest from that stock. The total supply after the natural stock is eliminated will be the same as in the case presented in section 2. However, the distribution of catch will differ, with more going to the salmon rancher.

The stability of the long run equilibrium is maintained as the salmon rancher adjusts his harvest rate to maximize profit. Assume the salmon rancher is in equilibrium with maximized profit and the fishery is in open access equilibrium. Suppose the fishermen assume that by increasing effort they can attain a new open access equilibrium and the salmon rancher will accept a lower profit rate. In this case, the salmon rancher must react by reducing salmon smolt release (i.e., increasing harvest) to maintain its profit maximizing position. When the salmon rancher does this, the increased effort by the fishermen will result in negative profits from ocean fishing. The system will shrink back to equilibrium as both fishermen and salmon rancher reduce fishing and harvesting effort, respectively.

5. Optimal Cooperative Management

In this section, the optimal cooperative management of a salmon ranching aquaculture facility and the natural fish stock is considered. The cooperative objective is to maximize the discounted profits from both operations,

$$\max_{H,E} \sum_{t=1}^{\infty} \alpha^{t-1}[R(H_t, E_t, W_t, X_t)] \tag{5.1}$$

subject to

$$X_{t+1} - X_t = f(X_t, E_t) - X_t \tag{5.2}$$

$$W_{t+1} - W_t = g(W_t, H_t, E_t) - W_t \tag{5.3}$$

$$0 \leq E \leq E_{max} \qquad 0 \leq H \leq H_{max}$$

Acknowledgment

The author is indebted to Marc Mangel, James Wilen, Joan Gray Anderson, and two anonymous referees for their valuabel comments.

Literature Cited

[1] J.E. Thorpe, The Development of Salmon Culture Towards Ranching (J.E. Thorpe, ed.), Academic Press, New York (1980).

[2] T. Edwin Cummings, "Private Salmon Hatcheries in Oregon," Oregon Dept. of Fish and Wildlife, Fish Division (1982).

[3] Michael Stratton, personal communication (1982).

[4] Robert L. Stokes, "The Economics of Salmon Ranching," Land Economics 38(4):464-477 (1982).

[5] J.A. Crutchfield and G. Pontecorvo, The Pacific Salmon Fisheries: A Study in Irrational Conservation, The Johns Hopkins University Press/Resources for the Future, Baltimore, MD (1969).

[6] R.J.H. Beverton and S.J. Holt, On the Dynamics of Exploited Fish Populations, United Kingdom Ministry of Agricultural Fisheries and Food, Fisheries Investigation Series 2(19) (1957).

[7] Colin Clark, Mathematical Bioeconomics, John Wiley and Sons, New York (1967).