Aquaculture, Capture Fisheries, and Wild Fish Stocks

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Abstract

In a general equilibrium model, this paper examines how the rise of aquaculture and the decline of wild fish stocks are related. Two factors, population growth and technological improvement in aquaculture, have been studied in an aquaculture restricted entry case and an aquaculture free entry case. Both factors raise aquaculture production, while changes in wild fish stocks hinge on entry conditions. In the restricted entry case, population growth reduces wild fish stocks, but technological progress in aquaculture raises them. In contrast, in the free entry case, only technological advance in aquaculture affects and raises wild fish stocks.

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1 Introduction

The depletion of wild fish stocks has been a serious issue for many years, since it threatens food security and may reduce long-term social welfare. The Food and Agriculture Organization (FAO) reports that just over half of the wild fish stocks (52 percent) are currently fully exploited and producing catches that are close to their maximum sustainable yields, while approximately one-quarter are overexploited, depleted or recovering from depletion (16 percent, 7 percent and 1 percent respectively). In contrast, world aquaculture production has grown rapidly in terms of both quantity and its relative contribution to world fish supplies (See Figure 1). Aquaculture, as an important protein source, now represents 5 percent of total animal protein supplies and the FAO predicts that by the year 2015 world aquaculture production will account for 39 percent of global fish production.

In this paper I investigate how the rise of aquaculture and the decline of wild fishery stocks are related. Specifically has the rise in aquaculture occurred because of the decline in wild fish stocks?; and can the current build up of aquaculture help repair the precarious state of many of the world's fisheries?

To address these questions, I focus on two factors thought to be responsible for the build up in aquaculture: population growth and technological progress.[1] An ever-increasing population always influences food-producing industries including aquaculture, and population growth in much of the developing world is quite high. The potential role of technological progress is less obvious, but supported by recent empirical work. For example, recent work by Huang and Qiao (2000) has shown that technological change in China is a key component of their aquaculture growth and China's growth is a large component of the growth shown in Figure 1.

To simplify, I focus on steady state outcomes throughout, and consider both a restricted entry and a free entry case. I develop a closed-economy model suited to developing countries since they play the dominant role in aquaculture production. For example, according to the FAO, in 2002 developing countries accounted for 90.7 percent of total aquaculture production in terms of quantity. Moreover, aquaculture production in developing countries had grown at an average annual rate of 10.4 percent from 1970 to 2002, while aquaculture production in developed countries had increased at an average annual rate of 4.0 percent.

Small scale producers in developing countries also typically rear environmentally friendly

[1] For instance, FAO (2001) published a study of aquaculture in a series of Asian countries, such as Bangladesh, China, India, etc. and mentioned that technological progress is a factor to stimulate aquaculture expansion in those countries.

herbivorous species, such as carp and tilapia which means the environmental and fish meal issues commonly discussed with regard to salmon or shrimp farming are entirely absent. Consequently, the focus here is on property rights differences across the two potential sources of fish supply. In aquaculture small scale producers own the means of production and harvest from private schools of fish; in contrast, property rights are absent or not fully enforced in most capture fisheries and this is certainly true in many developing countries. I highlight this difference across potential fish suppliers by assuming open access obtains in the capture fishery while aquaculture exhibits private ownership[2].

When entry into aquaculture is not possible, I find that population growth and technological progress in aquaculture have opposing effects on wild fish stocks and fish prices. Population growth drives up demand, raises fish prices and increases pressure on wild fish stocks. In contrast, technological progress tends to reduce fish prices and increases wild fish stocks by making their substitute (farmed fish) relatively easier to produce. With entry though, technological progress wins out in the end. In this case, the change in prices created by population growth leads to further entry driving profits in aquaculture to zero. As a result, in the free entry case, the industry supply curve for aquaculture is, in effect, flat and even though population growth raises demand it cannot influence fish prices nor wild fish stocks. With entry possible, the sole effect of population growth is to increase the share of aquaculture in total fish supplies, while technological progress in aquaculture lowers fish prices constant when protecting wild fish stocks.

In addition to the positive results mentioned above I also investigate the welfare consequences of various policies. I find that technological growth in aquaculture may increase (steady state) social welfare in the restricted entry case, while it unconditionally raises social welfare in the free entry case. Therefore progress in aquaculture could be a powerful method to alleviate poverty and enhance social well-being in many developing countries.

These results suggest a very positive role could be played by aquaculture in rebuilding wild fish stocks. At present, the problem of depleted wild stocks is met with precautionary fisheries management systems, vessel buy-back programs, unemployment insurance projects for fishermen, and fisheries subsidy reduction plans. While these policies have sometimes met with great success, there has also been notable failures. This paper suggests that aquaculture could play a significant role in the restoration of wild fish populations; it does so by altering the distribution of fish catch toward sources with more complete property rights

[2]The early literature often used the term 'common property' as if it implies 'open access'. However, it is now standard in resource economics to accurately use 'open access' that results in market failure.

- private aquaculture fish farms. It is also natural to think that given the better property rights in this sector, that technological progress in aquaculture could not only play a key role in restoring fish stocks but is likely to proceed at rapid rates given the returns from technological advance could be captured by private agents.

There is surprisingly little economic literature examining the interactions between aquaculture and capture fisheries despite its importance. The existing work can be divided into two groups. In the first group, the focus is on biological interactions between wild and farmed populations. For example, Anderson(1985a), and Anderson and Wilen(1986) examine the interaction between commercial fisheries and live capture farmed fish; Hannesson(2003) studies a two-species system of wild feed fish and edible farmed fish. The interactions here come from the competition for feed fish between farmed edible fish and wild edible fish. A second group of studies examines the market interactions between aquaculture and traditional fisheries. For example, Anderson(1985b) studies the consequences of the aquaculture entry on fish prices, while Ye and Beddington(1996) examine similar questions but assume farmed fish and wild fish are imperfect substitutes.

This paper differs from previous work in several ways. First, in contrast to earlier work this paper presents a general equilibrium model of aquaculture and capture fisheries. The general equilibrium setting facilitates our discussion of population growth and allows for an analysis of sectoral shifts in employment. Second, this paper focuses attention on how differences in property rights across wild and farmed fisheries determine the impact of population growth and technological progress. It highlights these differences by using both the restricted and free entry case, again new to the literature. Finally, I present a normative welfare analysis although this is limited to steady state utility comparisons.

The rest of the paper proceeds as follows. In section 2, the structure of fish growth is set out. Section 3 studies the production and supply functions of all the industries. Section 4 constructs the relative demand. In section 5 and 6, the restricted entry case and the free entry case are laid out separately. Section 7 contains concluding remarks.

2 The Structure of Fish Growth

Before we proceed to a general equilibrium model, it is worth describing the structure of fish growth. Fish stocks of both aquaculture and the capture fishery grow in a similar manner. The change in fish stock at time t is equal to natural growth $G(S(t))$ minus the harvest rates

$H(t)$. For aquaculture and the capture fishery respectively we have.

$$dS_A/dt = G(S_A(t)) - H_A(t) \tag{1}$$
$$dS_F/dt = G(S_F(t)) - H_F(t) \tag{2}$$

where S is the fish stock, the subscript A indicates an aquaculture firm, and the subscript F represents the capture fishery. Notice that A denotes variables at a firm level, and F denotes variables at an industry level.

To simplify, I assume the growth functions take the logistic form.

$$G(S_A) = r_A S_A(1 - S_A/K_A) \tag{3}$$
$$G(S_F) = r_F S_F(1 - S_F/K_F) \tag{4}$$

The positive constant r denotes the intrinsic growth rate, and the positive constant K is the carrying capacity. For $S = K/2$, G reaches the unique maximum point so-called 'maximum sustainable yield' (MSY) at point A in Figure 2.

The functional form of the harvest rate H must be derived from the economic incentives that control the behavior of harvesters. Since these incentives differ across industry I will discuss the incentives in aquaculture and the capture fishery separately.

3 Production and Supply

The economy has three production factors: the aquaculture fish stocks, the wild fishery fish stock, and labor. The fish stock in the capture fishery is subject to open access, and the fish stocks in aquaculture are privately owned by "aquaculturists". There are two consumer goods, a fish product and manufactures, and three industries, aquaculture, the capture fishery and manufacturing. I assume that wild and farmed fish are perfect substitutes, and there is no biological interaction between aquaculture and the capture fishery. The capture fishery and aquaculture compete in labor and fish markets which I assume are perfectly competitive.[3]

[3]If the capture fishery fish and aquaculture fish are not perfect substitutes, this paper's results only change slightly. (See for example the analysis in Ye and Beddington (1996))

3.1 Manufacturing

The manufactured good is the numeraire good, whose price is normalized to one. Manufacturing production exhibits constant returns and takes the following form.

$$M = L_m \tag{5}$$

where L_m is the amount of labor employed in manufacturing.

By choice of units the marginal product of labor is one in manufacturing. Thus, if manufactures are produced, the manufacturing price must equal the wage.

$$Numeraire\ price = 1 = W \tag{6}$$

3.2 The Capture Fishery

In the capture fishery every agent has access to the same production technology given by the canonical Schaefer harvesting production function.

$$H_F = \alpha_F S_F L_F \tag{7}$$

where L_F is the amount of labor employed in the capture fishery; α_F is a positive constant reflecting the technology level in the capture fishery.

It is useful to define the unit labor requirement in the capture fishery $a_{LF}(S_F)$. Using (7) we find

$$a_{LF}(S_F) = L_F/H_F = 1/(\alpha_F S_F) \tag{8}$$

Note that $a_{LF}(S_F)$ is monotonically declining in S_F reaching its minimum at $1/(\alpha_F K_F)$. Under open access, unit costs of production in the capture fishery are just $W/(\alpha_F S_F)$.

If we let P denote the relative price of fish, then if $P < W/(\alpha_F K_F)$ the capture fishery cannot exist. Fishermen's marginal cost of producing fish is higher than the fish price. If $P \geq W/(\alpha_F K_F)$, the capture fishery can exist, but if P is strictly above marginal costs, all labor would be in the capture fishery which is inconsistent with the production of both goods. Therefore, in autarky equilibrium prices must adjust so that positive production will occur and we have that $P = W a_{LF}(S_F) = W/(\alpha_F S_F)$. Rearranging

$$S_F = W/(\alpha_F P) \tag{9}$$

Note the negative relationship between the fish stock S_F and the fish price P.

In steady state, dS_F/dt equals zero. Combining (2) and (4) yields a relationship between the steady state harvest and stock as

$$H_F = G(S_F) = r_F S_F(1 - S_F/K_F) \tag{10}$$

For $S_F < K_F/2$, an increase in the fish stock raises the steady state harvest; in contrast, for $S_F > K_F/2$, an increase in the fish stock lowers the steady state harvest.

Finally it is useful to have a solution for the amount of labor employed in the capture fishery. To do so, combine (4) and (7) to find the steady state relationship between labor employed and the stock

$$L_F = H_F/(\alpha_F S_F) = (r_F/\alpha_F)(1 - S_F/K_F) \tag{11}$$

If we now combine (9), (10) and (11) we can solve for the steady state harvest, labor employed in the capture fishery, and its stock level taking as given P; that is, we can find the industry supply function for the capture fishery.[4]

3.3 A Representative Aquaculture Firm

The competitive aquaculture industry includes a large number of identical aquaculture firms. A representative firm in aquaculture has two operations: it produces and uses feed for its captive fish and it harvests them. A firm's instantaneous profit is simply revenues from harvesting minus its two sources of costs; specifically,

$$\pi = PH_A - WL_A - WL_{FD} \tag{12}$$

where L_A is the amount of labor employed in harvesting and L_{FD} is the amount of labor used in feed production.

I assume the production function for feed is constant returns. By choice of units each unit of the fish stock requires one unit of feed per unit time. Therefore, maintaining a stock of fish equal to S_A requires S_A units of feed at each instant in time. The supply of feed is created by labor effort and given by

$$Feed = \theta_A L_{FD} \tag{13}$$

where θ_A is a positive constant. Most farmed fish species in developing countries are herbivorous and hence their feed comes from agricultural products which we have implicitly

[4]The detail of the fishery industry problem can be found in Brander and Taylor (1997a).

assumed is produced under constant returns. I assume this production is done in house, but clearly the firm could purchase feed at its competitive price as well.

I assume there is a fixed cost each period in aquaculture together with constant marginal costs. The fixed cost includes the costs of maintaining ponds, storage sheds and aquaculture equipment, and administrative costs. Inverting this function to write it in terms of required labor input we have

$$L_A = F_A + (1/\alpha_A)H_A \tag{14}$$

where α_A is a positive constant representing the level of the harvesting technology; F_A is a positive fixed costs denominated in terms of labor input.

Substituting (13) and (14) into (12) yields instantaneous profits of a representative firm

$$\pi = (P - W/\alpha_A)H_A - F_A W - (W/\theta_A)S_A \tag{15}$$

Firms are identical, infinitely lived and take prices for inputs and outputs as given. The representative aquaculture firm maximizes the present value of its lifetime profit by solving the following problem.

$$\begin{array}{lrcl} Max_{H_A,S_A} & \int_0^\infty & e^{-\delta t}((P - \frac{W}{\alpha_A})H_A - WF_A - (\frac{W}{\theta_A})S_A)dt & \\ Subject\ to & dS_A/dt & = & G(S_A) - H_A; \quad G(S_A) = r_A S_A(1 - \frac{S_A}{K_A}); \\ & S_A(0) & = & S_{A0}: \qquad r_A > \delta \end{array} \tag{16}$$

where δ denotes the nonnegative discount rate; the assumption that $r_A > \delta$ assures that a positive stock exists in an aquaculture firm; the state variable S_A assumes a given initial value S_{A0}; and we note that since the economy's labor force is of finite size, the harvest at any point in time cannot exceed a certain maximum.

$$0 \leq H_A \leq H_{max}$$

The current value Hamiltonian for this problem is

$$H = ((P - \frac{W}{\alpha_A})H_A - \frac{W}{\theta_A}S_A - F_A W) + \lambda(G(S_A) - H_A)$$

According to optimal control theory, we need to maximize the current value Hamiltonian with respect to the control variable H_A. Since the Hamiltonian is linear in the control, the control variable takes extreme values, and we have a bang-bang solution.

$$\begin{array}{rcll} H_A & = & 0 & if\ \lambda > P - W/\alpha_A \\ H_A & = & H_{max} & if\ \lambda < P - W/\alpha_A \end{array} \tag{17}$$

When λ reaches $P - W/\alpha_A$, and stays this value over a positive time interval, then $d\lambda/dt = 0$. We have the singular control.

$$\lambda = P - W/\alpha_A$$
$$d\lambda/dt = \delta\lambda + W/\theta_A - \lambda G'(S_A) = 0 \tag{18}$$

Replacing λ with $P - W/\alpha_A$ in (18) gives the singular path of the fish stock.[5] Since $G'(S_A)$ deceases monotonically from r_A to $-r_A$, and aquaculturists treat other variables as constants, the unique solution of an optimal stock is implicitly given by.

$$[(P - W/\alpha_A)G'(S_A) - W/\theta_A]/\delta = (P - W/\alpha_A) \tag{19}$$

This marginal condition is very intuitive. The right hand side is the cost of a marginal increase in the fish stock represented by the current loss in revenue equal to $P - W/\alpha_A$. Pulling the fish out of the pond costs W/α_A in terms of labor and earns P in the market. The gap between these two is the opportunity cost of leaving the fish in place. The left hand side is the benefit from a marginal increase in the fish stock. A marginal increase in the stock increases the sustainable harvest from the stock by $G'(S_A)$ and this increase in the steady state harvest earns variable profits of $(P - W/\alpha_A)$ but requires the additional feed costs of W/θ_A per unit time. Equating these permanent benefits, in present value terms, to the current reduction in revenues on the right hand side identifies the optimal stock size.

The optimal path of the fish stock over an infinite time horizon can be obtained by combining the bang-bang solution and the singular solution. Aquaculturists harvest at the minimum or maximum value of the harvest rate in each period to drive the fish stock from the initial value S_{A0} to the singular solution S_A^*, and then maintain at the singular path of the fish stock forever. In steady state, we are on the singular path and can find by implication the optimal labor allocation to harvesting and feed production. These solutions, for any given price and wage combination, aggregated across firms gives us the industry supply curve.

3.4 The Stock in the Representative Aquaculture Firm

Using (19) it is fairly easy to show that

Lemma 1 *The optimal stock in aquaculture is less than the maximum sustainable yield stock* $K_A/2$.[6]

[5] The transversality condition holds, that is, $lim_{T\to\infty}\lambda(T)e^{-\delta T} = 0$, since $\lambda(T)$ is a constant, $P - W/\alpha_A$.
[6] A comparable solution can be found in Anderson J. L. (1985a).

Proof in the appendix. Graphically, the solution of the harvest is on the curve to the left of point A in Figure 2.

If $P - W/\alpha_A > 0$ and $r_A - W/(\theta_A(P - W/\alpha_A)) \geq \delta$, using lemma one we can now solve for what we now know is the unique solution of the optimal fish stock in a representative aquaculture firm.

$$S_A^*(P/W) = \frac{K_A}{2}(1 - \delta/r_A - \frac{1}{\theta_A r_A(P/W - 1/\alpha_A)}) \tag{20}$$

Note that the optimal stock is necessarily rising in the relative price of fish P, and since $S_A^* < K_A/2$, this implies the fish harvest is rising in the relative price.

The fact that the stock falls short of $K_A/2$ is due to two forces. First, harvesting costs are independent of the fish stock and hence treating the fish stock as an asset to be liquidated at any time yields the optimality condition $G'(S_A) = \delta$ which implies a stock less than $K_A/2$. For example from (20), we can eliminate the impact of feed costs by assuming the productivity in feed production were infinite (let $\theta_A \to +\infty$). In this case, the optimal stock only differs from $K_A/2$ by an extent determined by the discount rate versus the intrinsic rate of resource growth. (20) simplifies to $S_A^*(P/W) = \frac{K_A}{2}(1 - \delta/r_A)$. The higher the discount rate is the smaller the stock must be, and δ/r_A must be less than one for a positive stock to exist.

But even when the discount rate is zero, the optimal stock is below $K_A/2$. The reason is simply feed costs. Letting $\delta = 0$ in (20) shows that the presence of feed costs pushes the optimal stock lower. The importance of this result is that for any admissible discount rate, the optimal stock falls, and optimal harvest rises, with an increase in fish prices. Therefore the simplification of assuming a zero discount rate will alter the results only slightly.

3.5 The Aquaculture Firm Supply

For convenience, consider the zero discount rate case as this simplifies the determination of firm and industry supply tremendously.[7] To find supply first note that total costs (TC) for a representative aquaculture firm consists of three parts: the variable harvesting cost $(W/\alpha_A)H_A$, the fixed harvesting cost $F_A W$, and the feed cost $(W/\theta_A)S_A$.

$$TC = (W/\alpha_A)H_A + F_A W + (W/\theta_A)S_A \tag{21}$$

[7] If the discount rate is not equal to zero, then the steady-state situations are more complicated, but the solutions are qualitatively similar.

In steady state, $dS_A/dt = 0$ and $G(S_A) = H_A$ in (1). When the discount rate is zero, (19) simplifies to $(P - W/\alpha_A)\ (dH_A/dS_A) = W/\theta_A$. It implies marginal costs (MC) equal price in the following equation, since the aquaculture market is competitive.

$$\begin{aligned} P = MC = W/\alpha_A + (W/\theta_A)dS_A/dH_A \qquad Or \\ P/W = MC/W = 1/\alpha_A + (1/\theta_A)dS_A/dH_A \end{aligned} \tag{22}$$

(22) is the aquaculture firm supply. We know that $S_A \in [0, K_A/2)$. The harvest H_A is thus increasing in the fish stock S_A. In other words, $dH_A/dS_A = r_A(1 - 2S_A/K_A) > 0$ for $S_A \in [0, K_A/2)$. Notice if S_A equals zero, then $H_A = 0$, $dH_A/dS_A = r_A$ and $MC/W = 1/\alpha_A + 1/(\theta_A r_A)$. If S_A approaches $K_A/2$, dH_A/dS_A approaches zero and MC/W approaches infinity. The upward sloping SS curve in Figure 3 depicts the supply curve of a typical aquaculture firm.

4 Demand

I assume that a representative consumer with the Cobb-Douglas instantaneous utility function is endowed with one unit of labor.

$$u = f^{\beta} m^{1-\beta} \tag{23}$$

where f is individual consumption of the fish; m is individual consumption of manufactures, and the share of expenditure on fish β is strictly between 0 and 1.

The representative consumer maximizes utility at each moment and takes the price P and the wage W as given. The profits of aquaculture firms are assumed to be distributed equally in lump-sum fashion. The instantaneous budget constraint is

$$Pf + m = I = W + N\pi/L \tag{24}$$

where I is total income at time t; π is the instantaneous profit of an aquaculture firm; L is the labor endowment; N is the number of aquaculture firms.

Maximizing (23) subject to (24) yields the individual demand functions $f = \beta I/P$ and $m = (1-\beta)I$. Notice that aggregate demands for H and M are described as $F^C = fL; M^C = mL$. We have

$$F^C = \beta IL/P; \qquad M^C = (1-\beta)IL \tag{25}$$

The relative demand of fish to manufactures is then

$$F^C/M^C = \beta/((1-\beta)P) \tag{26}$$

5 The Aquaculture Restricted Entry Case

We first consider the restricted entry case with a fixed number of aquaculture firms N. Suppose N here is neither too large to drive profit to zero, nor too small to generate market power. The supply curve in aquaculture is the summation of the firms' MC curves.[8]

We assume three conditions on the steady state relative supply (RS). First, we assume that the capture fishery emerges before aquaculture. It requires the minimum of aquaculture firms supply $1/\alpha_A + 1/(\theta_A r_A)$ in Figure 3 be greater than or equal to the minimum of the unit labor requirement in the capture fishery $1/(\alpha_F K_F)$. Second, in light of the possible backward bending property of RS, we assume that the minimum of aquaculture firms' supply curve $1/\alpha_A + 1/(\theta_A r_A)$ has an upper bound $\bar{a}_{LA}$ so that aquaculture appears before RS bends backwards. ($\bar{a}_{LA} = 1/(\alpha_F K_F)[r_F/[(\alpha_F L(\alpha_F L - r_F))^{1/2} - (\alpha_F L - r_F)]]$. (See appendix.) Finally, in order to guarantee the existence of manufacturing at any relative price of fish, we assume the endowment of labor is large enough to produce manufactures at any prices.

The labor market clearance condition is

$$L = L_M + L_F + N(L_A + L_{FD}) \tag{27}$$

Accordingly, a sufficient condition for existence of manufactures is $L - Max(L_F) - N(Max(L_A) + Max(L_{FD})) > 0$, that is, $L > r_F/\alpha_F + N(r_A K_A/4\alpha_A + F_A + K_A/2\theta_A)$ from (11), (13), (14), and (27). We have the following lemma and proposition.

Lemma 2 *If $1/(\alpha_F K_F) \leq 1/\alpha_A + 1/(\theta_A r_A) \leq \bar{a}_{LA}$ and $L > r_F/\alpha_F + N(r_A K_A/4\alpha_A + F_A + K_A/2\theta_A)$, then the capture fishery emerges before aquaculture, aquaculture appears before the RS bends backward, and manufacturing always exists in the restricted entry case.*

Lemma 2 is reasonable. Although capture fisheries prevail for centuries, aquaculture in most of developing countries has developed and grown significantly since the 1970s. (See Figure 1) In addition, in most of developing countries, commonly raised species such as carp and tilapia have not reached their MSY. This implies that aquaculture appears before the RS bends backward. Clearly, manufacturing exists in almost all the developing countries.

Proposition 1 *With lemma 2 in place,*

1. *for $P < 1/(\alpha_F K_F)$, RS = 0.*

[8] Anderson's paper (1985b) has a comparable supply curve.

2. for $1/(\alpha_F K_F) \leq P < 1/\alpha_A + 1/(\theta_A r_A)$,

$$RS = \frac{(r_F/(\alpha_F P))(1 - 1/(\alpha_F P K_F))}{L - (r_F/\alpha_F)(1 - 1/(\alpha_F P K_F))} \tag{28}$$

3. for $P \geq 1/\alpha_A + 1/(\theta_A r_A)$,

$$RS = \frac{(r_F/(\alpha_F P))(1 - 1/(\alpha_F P K_F)) + N H_A(P)}{L - (r_F/\alpha_F)(1 - S_F(P)/K_F) - N(F_A + H_A(P)/\alpha_A + S_A(P)/\theta_A)} \tag{29}$$

$S_A(P) = (K_A/2)(1 - 1/(\theta_A r_A(P - 1/\alpha_A))$ *and* $H_A(P) = r_A S_A(P)(1 - S_A(P)/K_A)$

Proofs of all propositions are in the appendix.

Property rights differ between aquaculture and the capture fishery. Aquaculture exhibits private ownership, while the capture fishery lacks property rights. Thus, when the fish price increases, the production of fish in aquaculture increases monotonically. The situation in the capture fishery is not so clear. When the fish price is lower, the wild fish stock is higher than the MSY. An increase in the fish price enhances the number of fishermen and production in the capture fishery. However, when the fish price is high, the wild fish stock is lower than the MSY. Although an increase in the fish price attracts more fishermen into the capture fishery, the harvest declines due to the low wild fish stock.

The RS of fish in proposition 1 is reasonable. When the price of fish is low, an increase in the fish price raises the production in both aquaculture and the capture fishery, and reduces the production in manufacturing. The RS of fish, thus, is increasing on an interval of the low fish price. When the fish price is high, a rise in the price only increases production in aquaculture, and the production in the capture begins to decline. Although an elevated price still reduces the production in manufacturing, whether the RS of fish is increasing or decreasing hinges on the underlying parameter values. When the price of fish is extremely high, the wild fish stock is depleted and can not produce a large amount of fish. An increase in the fish price raises the production in aquaculture and reduces the production in manufacturing, so that the RS of fish is increasing. Mathematically, the RS is zero if P is zero. If P approaches infinity, the RS reaches a certain positive number, because H_F approaches zero, H_A reaches $K_A/2$, and M is a positive number. The RS curve in Figure 4 represents the relative supply. RD declines from infinity to zero, as P changes from zero to infinity.

Both the RD and RS are continuous, so that a solution of the relative price P^* exists. Furthermore, the solution of the relative price is unique. P^{na} denotes the relative fish price, where the RS curve without the aquaculture industry intersects the RD. (Point B or D in Figure 4).

$$\begin{aligned} P^{na} &= 1/[\alpha_F K_F(1-\alpha_F\beta L/r_F)] \qquad for\ \alpha_F\beta L < r_F \\ &= infinity \qquad for\ \alpha_F\beta L \geq r_F \end{aligned} \tag{30}$$

Because of the specific RD and RS functions, the solution P^{na} is unique, although the RS without aquaculture is backward bending. The RS with aquaculture (RS in Figure 4) does not bend backward as severely as the RS without aquaculture. Thus, the solution of the relative price is unique[9] as well. The RD and RS analysis leads to equilibrium solutions in the following proposition.

Proposition 2 *With lemma 2 in place,*

1. *for $P^{na} < 1/\alpha_A + 1/(\theta_A r_A)$, the relative fish price $P^* = P^{na}$ and $F/M = \beta/((1-\beta)P^{na})$. The capture fishery and manufacturing exist.*

2. *for $P^{na} \geq 1/\alpha_A + 1/(\theta_A r_A)$, there is a solution of the relative fish price at steady state P^*, (where can be obtained by $RD = RS$,) and $F/M = \beta/((1-\beta)P^*)$. Aquaculture, the capture fishery and manufacturing exist.*

We concentrate on the interesting case, where aquaculture, the capture fishery, and manufacturing coexist. After obtaining the solution of P^*, we can easily solve the whole model. Since aquaculture exists, the solutions in the aquaculture firm can be obtained by solving (13), (14) and (22). The steady-state profit in an aquaculture firm is the total revenue minus the total cost in (12). After knowing the relative price of fish P^* and the wage, we can solve for the solutions of the capture fishery from (9)-(11). (5) outlines the solutions in manufacturing.

5.1 Population Growth

We consider the comparative steady state effect of a change in population by focusing on the changes in the relative fish price P^*. (29) implies an increase in the labor L reduces

[9] In general function forms of RD and RS, we could obtain multiple solutions. However, Figure 4 shows if RS does not bend backward, (that is, as the fish price increases, the increase in aquaculture fish supply is greater than the possible decrease in capture fishery supply,) or if RD is flat, then it is likely to obtain a unique solution.

RS and raises the relative fish price P^*. From (22) we know that the elevated price always raises the production of aquaculture firms and total aquaculture production. However, in the capture fishery it is not so clear. If the original fishery stock is equal to or less than the MSY, the elevated price reduces the capture fishery production; if the original wild fish stock is above the MSY, it raises the capture fishery production. The magnitude of these production changes in aquaculture and the capture fishery relies on underlying parameter values. Therefore, if the wild fish stock is equal to or less than the MSY, the share of aquaculture in the overall fish supply increases, as population grows. And the result is ambiguous, if the capture fishery stock is above the MSY.

It is not surprising that population growth raises the relative fish price. Under recent situation of the wild fish stocks, where about three quarters of the wild fish stocks are close to or lower than their MSY, large population growth in developing countries seems to contribute significantly to recent rapid aquaculture growth and the substantial increase in the aquaculture share in the total fish supply in Figure 1.

5.2 Technology

Aquaculture has grown substantially since the 1970s, a result of both population increases in developing countries and improvements in technology. Technological improvements in aquaculture have been made in a number of areas, including feed quality and management, biotech, and disease control. It is worth studying the impact of better technology in at least two areas. Recall that α_A represents the level of harvesting technology in aquaculture, and θ_A reflects the technology level in feed production.

To proceed further, we define the technology elasticity of harvest in aquaculture $\epsilon_{H_A\alpha_A}$ as a percentage change in the aquaculture firm's harvest H_A that occurs in response to a percentage change in the harvest technology level α_A, when the fish price is held constant. Similarly, the feed technology elasticity of aquaculture stock $\epsilon_{S_A\theta_A}$ is defined as a percentage change in the aquaculture firm's stock S_A that occurs in response to a percentage change in the feed technology level θ_A, when the fish price is held constant.

Proposition 3 *In the restricted entry case,*

1. *if the technology elasticity of harvest in aquaculture $\epsilon_{H_A\alpha_A}$ is greater than or equal to one, then the relative price of fish P^* decreases, and the harvest in an aquaculture firm and the total harvest in aquaculture increase as the harvesting technology α_A advances.*

2. *if the feed technology elasticity of aquaculture stock $\epsilon_{S_A\theta_A}$ is greater than or equal to one, then the relative price of fish P^* decreases, and the harvest in an aquaculture firm and the total harvest in aquaculture increase as the technology of feed production θ_A improves.*

When harvesting technology in aquaculture α_A advances, under the condition that $\epsilon_{H_A\alpha_A} \geq 1$, aquaculture labor inputs in harvest and feed production rise, and labor input in manufacturing falls. This means that given the fish price, the production of fish increases while the production of manufacturing decreases, implying that the RS rises. The RD is not altered by harvesting technology growth, and the fish price decreases. Similarly, when the feed technology improves, under the condition that $\epsilon_{S_A\theta_A} \geq 1$, the RS of fish rises, the RD of fish does not change, and the fish price drops. The proof of the increase in the total aquaculture harvest is more complex and is shown in the appendix.

It is reasonable that an increase in harvest or feed technology in aquaculture enhances aquaculture production and reduces the fish price. The more interesting feature of the model is that when P^* declines, the wild fish stock rises in (9). Therefore, technology growth in aquaculture could be a key factor to ameliorate the depletion of the wild fish stocks in the future.

The change in the aquaculture share of total fish supply is unclear. In proposition 3, technological improvement in aquaculture reduces the fish price and raises the total harvest in aquaculture. However, the harvest change in the capture fishery is ambiguous. If the wild fish stock is over the MSY, the lower price reduces the production in the capture fishery so that the share of aquaculture in total fish supplies increases. If the wild fish stock is equal to or less than the MSY, the lower price raises the production in the capture fishery. Consequently, the share of aquaculture in total fish supplies may increase or decrease due to ambiguous changes in the capture-fishery production.

When we consider population growth and technological progress together, the changes of the fish price and the wild fish stock are unclear. Both population growth and technological progress in aquaculture affect the fish price and the wild fish stock, but in the opposite directions. Population growth increases the fish price and reduces the wild fish stock, while technological improvement in aquaculture decreases the fish price and raises the wild fish stock. Underlying parameter values determine which factor dominates population growth or technological improvement.

In reality, increasing fish prices and depleted wild fish stocks may imply that population growth is the dominant factor; in this case, fish stocks would not be restored if entry were restricted. However, technology growth in aquaculture could be a key factor in ameliorating the depletion of the wild fish stocks in the future.

5.3 Welfare Analysis of Better Aquaculture Technology

Aquaculture not only supplies an important source of protein in many countries; it also contributes to poverty alleviation and an improvement of social well-being. As a key generator of aquaculture growth, better aquaculture technology improves social welfare at a steady state in this model, other things being equal. From proposition 3, we have the following proposition.

Proposition 4 *In the restricted entry case,*

1. *if the technology elasticity of harvest in aquaculture $\epsilon_{H_A \alpha_A}$ is greater than or equal to one, then the steady state social welfare increases as the harvesting technology α_A advances.*

2. *if the feed technology elasticity of aquaculture stock $\epsilon_{S_A \theta_A}$ is greater than or equal to one, then the steady state social welfare increases as the technology of feed production θ_A improves.*

Although the proof in the appendix is complex, proposition 4 is meaningful. As the fastest-growing food-producing industry, aquaculture, which is largely located in rural areas in developing countries, has begun to play a significant role in helping the poor out of their social and economic plight. This paper suggests that with on-going technological improvements, aquaculture would be an effective method to improve social welfare and to alleviate poverty.

6 The Aquaculture Free Entry Case

6.1 Solutions in Aquaculture

In the free entry aquaculture case, the zero-profit condition holds, since free entry and exit drive profits to zero in each aquaculture firm.[10] The zero profit condition implies that the fish price equals the average cost (AC) in a representative aquaculture firm.

[10]The zero profit condition is a good approximation as long as there is a large number of firms in aquaculture.

From the total cost equation (21), we have the average cost

$$P = AC = W/\alpha_A + WF_A/H_A + (W/\theta_A)(S_A/H_A) \qquad Or$$
$$P/W = AC/W = (1/\alpha_A) + F_A/H_A + (1/\theta_A)(S_A/H_A) \tag{31}$$

In Figure 3, the U-shaped CC curve indicates the AC/W curve.

In (31), AC includes three components: the constant average variable harvesting cost W/α_A, the decreasing average fixed harvesting cost WF_A/H_A, and the increasing average feed cost $(W/\theta_A)(S_A/H_A)$. The increasing average feed cost can be shown clearly as follows. We know that the aquaculture firm produces when the fish stock is at the fish stock $S_A \in [0, K_A/2)$. In Figure 1, the horizontal distance over the vertical distance is increasing in H_A, that is, S_A/H_A is increasing in H_A. The average feed cost is increasing in H_A as well. The average fixed cost is decreasing in H_A from negative infinity to zero as usual. Thus, AC is U-shaped owing to the increasing average feed cost and the decreasing average fixed harvesting cost.

There are only two possible solutions for H_A in the free entry case. $(P/W)^*$ denotes the critical value of the price-wage ratio when the representative aquaculture firm have zero profit. The first solution is that, for $P/W < (P/W)^*$, aquaculture firms' profits are negative, so that aquaculture firms do not operate and H_A equals zero. The second solution is that, for $P/W = (P/W)^*$, the aquaculture firm produces a positive amount of fish. In the free entry case, P/W can not be greater than $(P/W)^*$. If this condition holds, a typical aquaculture firm has positive profit, which violates the free entry assumption.

Graphically point A in Figure 3 shows the unique critical value of $(P/W)^*$ and the unique optimal interior solutions of $H_A(S_A^*)$. We know the MC curve must pass through the minimum point of the AC curve. Consequently, the unique interior solution of $(P/W)^*$ must be the minimum value of the AC curve.

Combining the marginal cost equation (22) and the average cost equation (31) yields

$$S_A^2 + 2F_A\theta_A S_A - F_A\theta_A K_A = 0$$

The positive solution of the fish stock in a representative aquaculture firm S_A^* can be solved.

$$S_A^* = (F_A^2\theta_A^2 + F_A\theta_A K_A)^{1/2} - F_A\theta_A \quad and \quad 0 < S_A^* < K_A/2. \tag{32}$$

It is straightforward that $S_A^* > 0$ in (32) because F_A, θ_A, K_A are assumed to be positive. Moreover, it can be shown that $S_A^* < K_A/2$.[11] At steady state, the harvest rate in a

[11]since K_A is positive, $K_A/2 + F_A\theta_A > (F_A^2\theta_A^2 + F_A\theta_A K_A)^{1/2}$. This means $S_A^* < K_A/2$

representative aquaculture firm equals the natural fish growth. Substituting S_A^* into (3) yields the solution of the optimal harvest rate $H_A(S_A^*) = G(S_A^*)$. We substitute S_A^* into the average cost equation (31) and obtain a unique critical value of $(P/W)^*$.

Since in (32) S_A^* is a constant, the aquaculture industry exhibits constant returns to scale. When the amount of labor in aquaculture increases x times, the harvest and the labor input in a representative aquaculture firm do not change. Accordingly, the number of firms and the total harvest in aquaculture increase x times. In other words, a new firm entering the market with duplicate production facilities expands the total output in aquaculture. Furthermore, the aquaculture supply curve should be flat if there is free entry in the aquaculture market.

For convenience, I assume a unique critical value of $(P/W)^*$ is the unit labor requirement in aquaculture, a_{LA}.

$$a_{LA} = (P/W)^* = 1/\alpha_A + 1/(\theta_A r_A(1 - 2S_A^*/K_A)) \tag{33}$$

Moreover, we are not able to solve the number of firms in aquaculture until we have the market clearance conditions.

6.2 The Equilibrium

To drive the RD, we assume three conditions. For the purpose of harmonizing analysis, the free entry case shares two conditions with the restricted entry case, and the third condition causes no conflict between the free and restricted entry cases. The first condition is the same as before: the minimum of aquaculture firms supply $1/\alpha_A + 1/(\theta_A r_A)$ is greater than or equal to the minimum of the unit labor requirement in the capture fishery $1/(\alpha_F K_F)$ so that the capture fishery emerges before aquaculture. We also know that the unit labor requirement in aquaculture a_{LA} is greater than the minimum of aquaculture firms supply $1/\alpha_A + 1/(\theta_A r_A)$. Thus, the unit labor requirement in aquaculture is also greater than the minimum of the unit labor requirement in the capture fishery $1/(\alpha_F K_F)$. The second condition is a new restriction that an upper limit of the unit labor requirement in aquaculture a_{LA} is $\bar{a}_{LA}$ so that aquaculture appears before the RS bends backwards, thus permitting a unique solution of the fish price. Finally, the condition common to both cases is that the labor endowment is large enough to guarantee the existence of manufacturing at any relative price of fish, that is, $L > r_F/\alpha_F + N(r_A K_A/4\alpha_A + F_A + K_A/2\theta_A)$. We have the following lemma and proposition.

Lemma 3 *If $1/(\alpha_F K_F) \leq 1/\alpha_A + 1/(\theta_A r_A)$, $a_{LA} \leq \bar{a}_{LA}$ and $L > r_F/\alpha_F + N(r_A K_A/4\alpha_A + F_A + K_A/2\theta_A)$, then the capture fishery emerges before aquaculture, aquaculture appears before RS bends backward, and manufacturing always exists in the free entry case.*

Arguably lemma 3 is as reasonable as lemma 2.

Proposition 5 *With lemma 3 in place,*

1. *for $0 \leq P < 1/(\alpha_F K_F)$, the relative supply is $F^P/M^P = 0$.*
2. *for $1/(\alpha_F K_F) \leq P < a_{LA}$, the relative supply is*

$$F^P/M^P = [r_F/(\alpha_F P)][1 - 1/(\alpha_F P K_F)]/[L - (r_F/\alpha_F)(1 - 1/(\alpha_F P K_F))] \tag{34}$$

   which is confined in the increasing portion.

3. *for $P = a_{LA}$, the relative supply is $P = a_{LA}$ and $F^P/M^P \in [[r_F/(\alpha_F a_{LA})][1 - 1/(\alpha_F a_{LA} K_F)]/[L - (r_F/\alpha_F)(1 - 1/(\alpha_F a_{LA} K_F))], \infty)$*

Although the proof is complex, the economic logic is simple. People choose the most efficient method to produce identical fish. The smaller the unit labor requirement is, the more efficient the industry is. Under a certain price $P = 1/(\alpha_F K_F)$, the capture fishery emerges. When the relative price of fish is between $1/(\alpha_F K_F)$ and a_{LA}, only the capture fishery provides fish since it has a unit labor requirement lower than aquaculture. If the relative price of fish equals a_{LA}, the unit labor requirements are equalized in two fishery industries, and both aquaculture and the capture fishery produce fish. The fish price can not move higher than a_{LA}, since new entrants in aquaculture will keep the price at a_{LA}. The RS curve in Figure 4 represents the relative supply in the free entry case. We obtain equilibrium solutions by combining the RD and the RS.

Proposition 6 *With lemma 3 in place,*

1. *for $P^{na} < a_{LA}$, the relative fish price in autarky at steady state $P^A = P^{na}$ and $F/M = \beta/((1-\beta)P^{na})$. The capture fishery and manufacturing exist.*
2. *for $P^{na} \geq a_{LA}$, the relative fish price in autarky at steady state $P^A = a_{LA}$ and $F/M = \beta/((1-\beta)a_{LA})$. Aquaculture, the capture fishery and manufacturing exist.*

P^{na} is the steady state relative fish price in autarky when aquaculture does not exist in (30).

The proof is similar to the proof in proposition 2. For $P^{na} \geq a_{LA}$, the intersection of the relative demand and the relative supply, as point C in Figure 4, is on the horizontal portion of the relative supply.

We only consider the case where aquaculture, the capture fishery, and manufacturing coexist. We solve for the remaining variables in the model. Since aquaculture does exist, the solutions of the representative aquaculture firm are obtained directly in section 6.1. The other variables, except the number of firm N, can be solved as in the restricted entry case.

We can use the labor and manufactures market clearance conditions to obtain the number of aquaculture firms. We combine the labor market clearance condition and the manufactures market clearance condition and solve N by.[12]

$$L_M = L - L_F(S_F(a_{LA})) - N(L_A(S_A^*) + L_{FD}(S_A^*)) = (1-\beta)L \tag{35}$$

6.3 Population Growth and Aquaculture Technology Growth

We analyze the comparative steady state in the case where aquaculture and the capture fishery coexist. Unlike the restricted entry case, an increase in the endowment of labor L has no effect on the fish price P^*, since P^* is determined by aquaculture. However, population growth leads to an increase in the share of aquaculture in fish supply. When L increases, the harvest in the capture fishery does not change since the fish price does not change. Yet, (35) implies that the number of firms rises so that the total harvest in aquaculture grows, and the aquaculture share of total fish supplies rises.

In the free entry case, the result that population growth can not alter the fish price is important. This result suggests that, when aquaculture exists, the ever-increasing population can not deplete the wild fish stock completely. It is reasonable to conclude that the entry of additional firms in aquaculture can help stabilize the fish price and maintain the wild fish stock.

To analyze the technology changes in aquaculture, we first consider how technological changes affect the unit labor requirement in aquaculture a_{LA} and the fish price P^*.

Proposition 7 *If aquaculture, the capture fishery and manufacturing coexist, then an increase in harvesting productivity α_A or an increase in feed productivity θ_A lower the unit*

[12]Aquaculture is assumed to have a large number of firms, N. To be rigorous, N should be an integer. Nonetheless, if N is large enough, an approximation could be obtained by the above equations.

labor requirement in aquaculture a_{LA} and the fish price P^* at steady state.

This result is similar to the restricted entry case, but proposition 7 holds without any additional assumptions. Moreover, the decrease in the fish price raises the natural fish stock in the capture fishery.

The total effects of population growth and technological progress in aquaculture on the wild fish stock differ between the restricted entry case and free entry case. In the restricted entry case, the wild fish stocks will not recover, if population growth plays a dominant role. However, this paper proposes that, in the free entry case, population growth has no impact on the wild fish stock, and technological improvement in aquaculture will definitely increase the wild fish stock. Thus, we should be optimistic about the future of wild fish stocks. Meanwhile, we should keep investing in aquaculture technology.

Technology growth in aquaculture raises the harvest in aquaculture and may raise or reduce the harvest in the capture fishery. Technological progress in aquaculture reduces the fish price and labor input in the capture fishery. We combine the labor market clearance condition and the manufactures market clearance condition and have $\beta L - L_F = N(L_A + L_{FD})$. Because of a decrease in labor input in the capture fishery, we know labor input in aquaculture must increase, so that the harvest in aquaculture rises as well. However, if the original wild fish stock is equal to or less than maximum sustainable yield, the decreased price enhances the capture fishery production, whereas if the original wild fish stock is above maximum sustainable yield, it reduces the capture fishery production.

Furthermore, technology growth in aquaculture definitely gives rise to steady-state social welfare gains because the real wage in terms of manufactures W does not change, while the real wage in terms of fish W/P^* increases at steady state. Thus, in the free entry case technological advance is also a method to alleviate poverty and to enhance living standards.

7 Conclusion

This paper investigates how the rise of aquaculture and the decline of wild fish stocks are related, using a two-good general equilibrium model. I highlight property rights differences between aquaculture and capture fisheries and study the market interaction between these two fishery industries. The focus of this paper is on steady state analysis of two important factors for aquaculture prosperity: population growth and technological progress. I distinguish the analysis between an aquaculture restricted case and an aquaculture free entry case, and I also present a normative welfare analysis although this is limited to steady state utility comparisons.

In the restricted entry case, population growth and technological improvement in aquaculture have opposite impacts on wild fish stocks. Population growth raises fish prices and reduces wild fish stocks, while technological progress in aquaculture reduces fish prices and increases wild fish stocks. Therefore, the direction of the change in wild fish stocks depends on which factor dominates. In regard to production, both population growth and technological improvement in aquaculture enhance the harvest in aquaculture, but the harvest in the capture fishery may rise or fall.

In the free entry case, population growth has no effect on fish prices and wild fish stocks, while technological progress in aquaculture reduces fish prices and restores wild fish stocks. Moreover, population growth raises aquaculture production but has no effect on capture fishery production. In contrast, technological advance in aquaculture raises aquaculture harvest, but the effect on capture fishery production is ambiguous and depends on original wild fish stocks.

This paper provides the following useful predictions and suggestions. Currently, increasing fish prices and depleted wild fish stocks imply that population growth rather than technological progress is a dominant factor in the stimulation of aquaculture growth in many developing countries. Fish stocks can not be restored due to significant population growth, when entry is limited in aquaculture. However, my theory suggests that, when free entry is possible, the ever-increasing population in developing countries will not deplete wild fish stocks completely due to the entry of additional firms into aquaculture. This entry can help stabilize fish prices and maintain wild fish stocks. Furthermore, technology growth in aquaculture could be a key factor to ameliorate the depletion of wild fish stocks, to alleviate poverty and to improve social welfare regardless of entry conditions. Thus, we should be optimistic about the future of wild fish stocks. Meanwhile, we should keep investing in aquaculture technology.

This paper only concentrates on a closed economy. Future work can be extended to incorporate international trade, since international trade plays a significant role in current fishery industries.

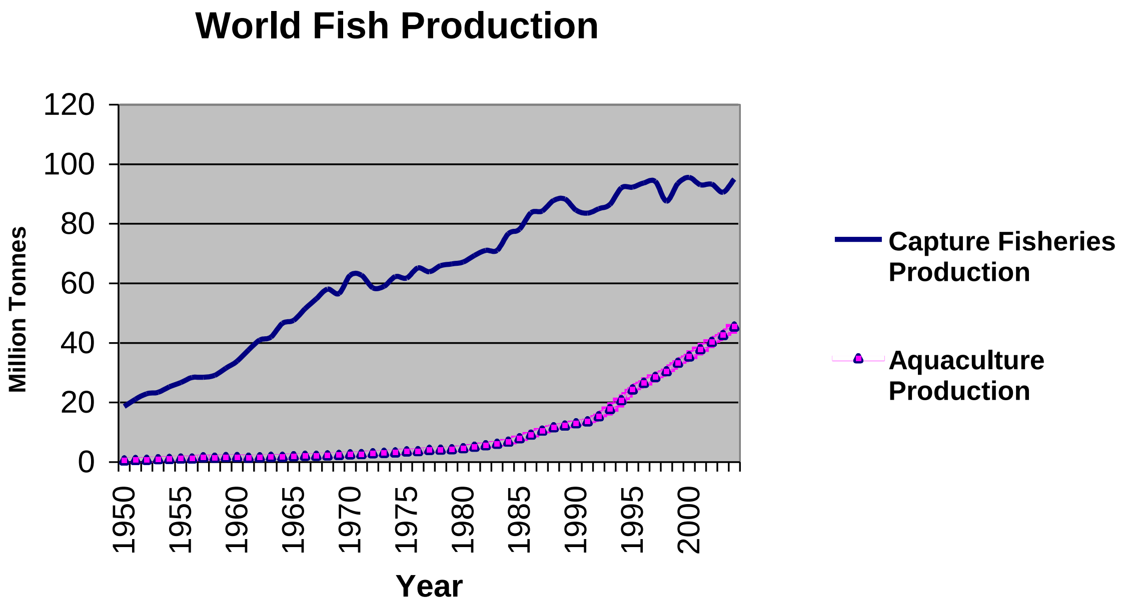

Figure 1: World Fish Production

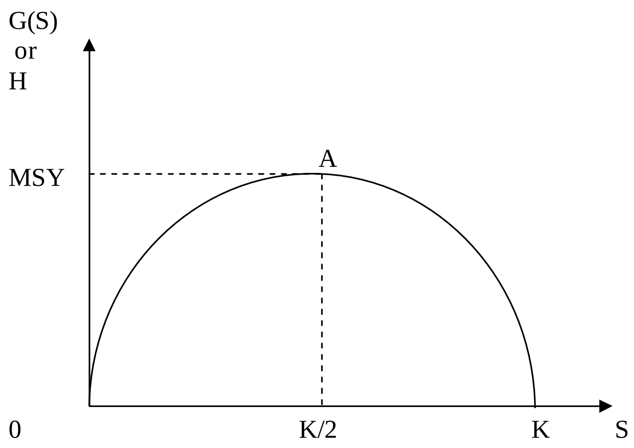

Figure 2: Fish Growth Function

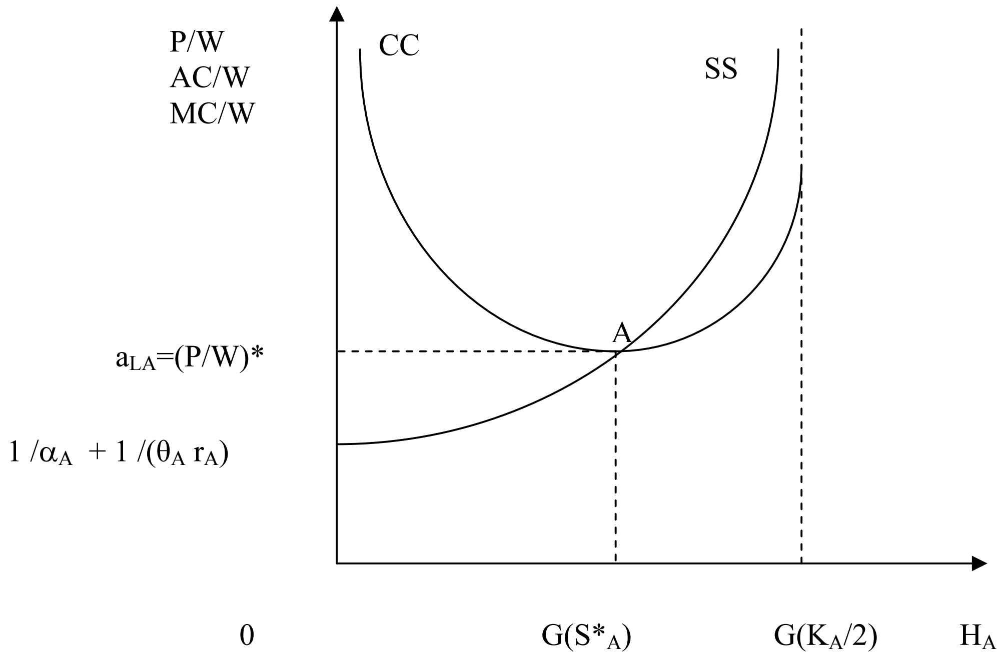

Figure 3: MC and AC

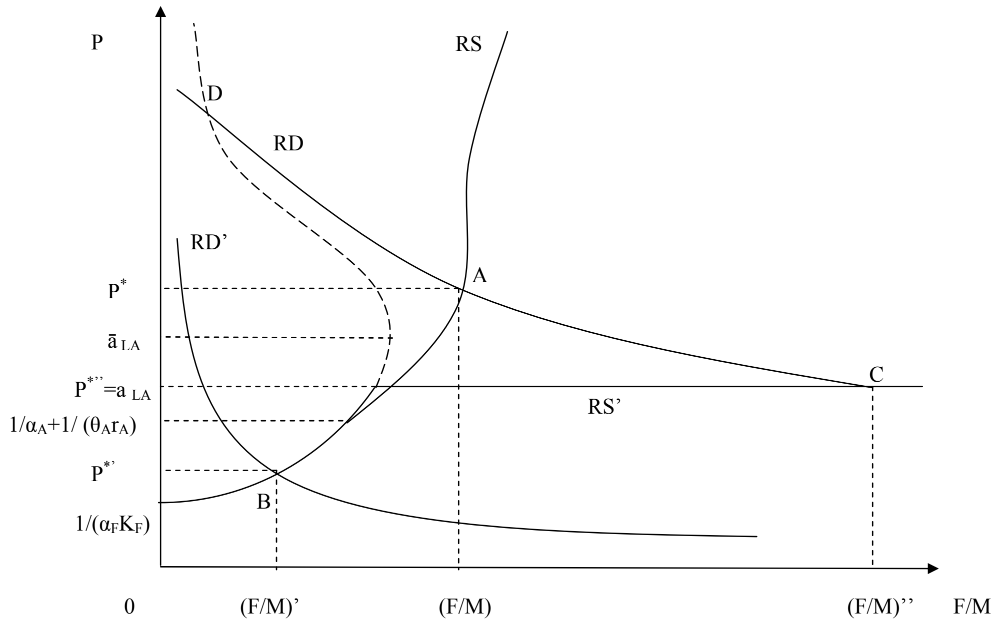

Figure 4: Equilibrium

Appendix

Proof: Lemma 1 To verify note that W and θ_A are assumed to be positive, and δ is nonnegative. If $P - W/\alpha_A > 0$ and $r_A - W/(\theta_A(P - W/\alpha_A)) \geq \delta$, (19) implies that $0 \leq S_A^* < K_A/2$. If $P - W/\alpha_A > 0$ and $r_A - W/(\theta_A(P - W/\alpha_A)) < \delta$, (19) has no solution. In such cases it follows that the optimal fish stock equals zero. If $P - W/\alpha_A \leq 0$, the firm's profit is negative in any period in (15) so that the aquaculture firm does not operate, and the fish stock is assumed to be zero.Δ

Proof: $\bar{a}_{LA} = 1/(\alpha_F K_F)[r_F/[(\alpha_F L(\alpha_F L - r_F))^{1/2} - (\alpha_F L - r_F)]]$

$\bar{a}_{LA}$ is the fish price where $d(F^P/M^P)/dP = 0$ when aquaculture does not exist. Because of Lemma 2 or 3, manufacturing always exists so that $W = 1$.

From (4) and (27), without aquaculture, we have

$$F^P/M^P = r_F S_F(1 - S_F/K_F)/[L - (r_F/\alpha_F)(1 - S_F/K_F)] \qquad (A1)$$

Differentiate (A1) with respect to S_F.

$$d(F^P/M^P) = \frac{1}{L - (r_F/\alpha_F)(1 - S_F/K_F)}[-(F^P/M^P)(r_F/\alpha_F K_F) + r_F(1 - 2S_F/K_F)]dS_F \qquad (A2)$$

We know $1/[L - (r_F/\alpha_F)(1 - S_F/K_F)] > 0$ due to the existence of manufacturing.

Differentiate $S_F = 1/\alpha_F P$ with respect to P. $dS_F = -1/(\alpha_F P^2)dP$ and $-1/(\alpha_F P^2) < 0$.

$\bar{a}_{LA}$ is the fish price where $d(F^P/M^P)/dP = 0$. Then, we have

$$-(F^P/M^P)(r_F/\alpha_F K_F) + r_F(1 - 2S_F/K_F) = 0 \qquad (A3)$$

Simplifying (A3) yields

$$[r_F/(K_F(\alpha_F L - r_F))]S_F^2 + 2S_F - K_F = 0 \qquad (A4)$$

Because manufacturing always exists, we have $\alpha_F L > r_F$, and the positive solution of S_F is $[K_F[(\alpha_F L(\alpha_F L - r_F))^{1/2} - (\alpha_F L - r_F)]]/r_F$. Substituting this into $P = 1/\alpha_F S_F$ yields

$\bar{a}_{LA} = 1/(\alpha_F K_F)[r_F/[(\alpha_F L(\alpha_F L - r_F))^{1/2} - (\alpha_F L - r_F)]]$ Δ

Proof: Proposition 1

For $P < 1/(\alpha_F K_F)$, the labor wage available in manufactures is equal to 1, and it is greater than the wage available in the capture fishery $\alpha_F K_F P$ and in aquaculture $P/(1/\alpha_A + 1/(\theta_A r_A))$. Only manufactures are produced, and neither aquaculture nor the capture fishery exist, i.e. $F^P/M^P = 0$.

Similarly, for $1/(\alpha_F K_F) \leq P < 1/\alpha_A + 1/(\theta_A r_A), W = 1 = \alpha_F S_F P > P/(1/\alpha_A + 1/(\theta_A r_A))$. Aquaculture does not exist. $F^P/M^P = H_F/M = [r_F S_F(1 - S_F/K_F)]/[L - (r_F/\alpha_F)(1 - S_F/K_F)]$ from (4), (10), (11) and (27). From (9) we have $F^P/M^P = [r_F/(\alpha_F P)][1 - 1/(\alpha_F P K_F)]/[L - (r_F/\alpha_F)(1 - 1/(\alpha_F P K_F))]$. Notice the sufficient condition for existence of manufactures, $L > r_F/\alpha_F + N(r_A K_A/4\alpha_A + F_A + K_A/2\theta_A)$, guarantees that the denominator is positive.

For $P \geq 1/\alpha_A + 1/(\theta_A r_A), W = 1 = \alpha_F S_F P = P/(1/\alpha_A + 1/(\theta_A dH_A/dS_A))$. Aquaculture, the capture fishery and manufacturing coexist. $RS = F^P/M^P = (H_F + NH_A)/M$. From (4), (9), (22), and 27, we have (29).Δ

Proof: Proposition 2

Using the relative supply and the relative demand in (26) and (28), we can obtain the unique solution of P^{na}, which is the relative fish price when aquaculture does not exist. For $\alpha_F \beta L < r_F$, the positive steady state stock exists, and $P^{na} = 1/[\alpha_F K_F(1 - \alpha_F \beta L/r_F)] > 0$. The condition is actually a condition on $G'(0)$ in the capture fishery where $G'(0) = r_F$. $G'(0)$ must be larger than $\alpha_F \beta L$ to guarantee the existence of a positive wild fish stock. Brown (1974), and Clemhout and Wan (1991) have comparable conditions. When aquaculture does not exist, for $\alpha_F \beta L \geq r_F$, harvest drives the wild fish stock to extinction under the Cobb-Douglas utility, and the relative fish price P^{na} approaches infinity.

If $P^{na} < 1/\alpha_A + 1/(\theta_A r_A)$, the intersection of RD and RS, as point B in Figure 4, is lower than $1/\alpha_A + 1/(\theta_A r_A)$. If $P^{na} \geq 1/\alpha_A + 1/(\theta_A r_A)$, RD and RS intersect at point A in Figure 4. (P^{na} is at point D in Figure 4.) Aquaculture, the capture fishery, and manufacturing coexist.Δ

Proof: If the solution of aquaculture fish stock is small, it is likely that $\epsilon_{H_A \alpha_A} \geq 1$ and $\epsilon_{S_A \theta_A} \geq 1$ in proposition 3.

$\epsilon_{H_A \alpha_A} = (dH_A/d\alpha_A)(\alpha_A/H_A) = (dH_A/dS_A)(dS_A/d\alpha_A)(\alpha_A/H_A)$

since $S_A = (K_A/2)[1 - 1/(\theta_A r_A(P - 1/\alpha_A))]$

$\epsilon_{H_A\alpha_A} = K_A/[2H_A\theta_A^2 r_A\alpha_A(P-1/\alpha_A)^3]$ given the fish price.

If S_A is small, H_A is small due to the positive relationship between them, and then, $\epsilon_{H_A\alpha_A}$ is large and could be greater than or equal to one.

For example, we take the free entry case, where $S_A^* = (F_A^2\theta_A^2 + F_A\theta_A K_A)^{1/2} - F_A\theta_A$ and $(P/W)^* = 1/\alpha_A + 1/(\theta_A r_A(1-2S_A^*/K_A))$. If F_A approaches zero, S_A^* and H_A^* are close to zero and P approaches $1/\alpha_A + 1/(\theta_A r_A)$. Therefore, $\epsilon_{H_A\alpha_A}$ approaches infinity and is greater than one. The proof of $\epsilon_{S_A\theta_A} \geq 1$ is similar. Δ

Proof: Proposition 3.

As α_A increases, the fish stock and harvest in aquaculture S_A and H_A increases in the MC function, holding the fish price constant. Under the condition that $\epsilon_{H_A\alpha_A} \geq 1$, aquaculture labor inputs in harvest and feed production, L_A and L_{FD}, rise in (13) and (14). Thus, the RS increases in (29). In addition, RD does not change. P^* decreases. The proof of the first part of 2 is similar.

Combining the labor market clearance condition (27) and the manufacturing market clearance condition (25) yields

$$L = (1-\beta)(L + N\pi) + L_F + N(L_A + L_{FD})$$

We substitute the profit function (12) and production functions (13)-(14) into π, L_A and L_{FD}

$$\beta L = (1-\beta)NPH_A + \beta N(F_A + H_A/\alpha_A + S_A/\theta_A) + L_F$$

We consider α_A first. Differentiate the above equation with respect to α_A.

$$dH_A/d\alpha_A = \frac{\beta NH_A/\alpha_A^2 - (1-\beta)NH_A dP/d\alpha_A - dL_F/d\alpha_A}{(1-\beta)NP + \beta N/\alpha_A + \beta N/\theta_A dS_A/dH_A} \qquad (A6)$$

We know technological improvement in aquaculture would reduce the fish price and the labor input in the capture fishery, that is $dP/d\alpha_A < 0, dL_F/d\alpha_A < 0$. We also know $dS_A/dH_A > 0$ because the fish stocks in aquaculture firms is less than $K_A/2$. Thus, $dH_A/d\alpha_A > 0$ in (A6). Similarly, we can obain $dH_A/d\theta > 0$. The total harvest in aquaculture is NH_A, which moves with H_A. Δ

Proof: Proposition 4

In (24), the individual budget constraint before the technological improvement is

$$P^B f^B + m^B = W + N\pi^B/L$$

where the superscript B denotes before-change.

After the technological improvement, a lump-sum transfer guarantees that the individual is able to purchase the same bundle as before. (The after-improvement consumption bundle is revealed preferred to the before-improvement bundle.)

$$Pf + m = W + N\pi/L + r$$

$$r = (P - P^B)f^B - N/L(\pi - \pi^B)$$

r is the lump-sum transfer for one individual.

$$government \;\; revenue = -Lr = N(\pi - \pi^B) + (P^B - P)F^B$$

where F^B is the total consumption of fish before the technological improvement. (The first term could be viewed as the producer surplus change, and the second term could be the consumer surplus change, although we use a general equilibrium model.)

From proposition 3, we know P^* decreases when α_A advances, in other words, $P^B > P$. $\pi - \pi^B$ is the change in producer surplus (PS) in an aquaculture firm. It is greater than the producer surplus gain under the new price $PS(P) - PS^B(P)$ minus $(P^B - P)H_A^B$.

Government revenue $> N(PS(P) - PS^B(P)) - N(P^B - P)H_A^B + (P^B - P)F^B$. Since the fish consumption is greater than the fish production in aquaculture, $(P^B - P)F^B - (P^B - P)NH_A^B > 0$. Thus, government revenue is positive and the steady state social welfare increases. The proof of 2) is similar. Δ

Proof: Proposition 5

We prove the relative supply curve.

For $P < 1/(\alpha_F K_F) < a_{LA}$, the labor wage available in manufactures is equal to 1 and is greater than the wage available in the capture fishery $\alpha_F K_F P$ and in aquaculture P/a_{LA}. Workers move in manufacturing and neither aquaculture nor the capture fishery exists, i.e. $F^P/M^P = 0$.

For $1/(\alpha_F K_F) \leq P < a_{LA}, W = 1 = \alpha_F S_F P > P/a_{LA}$. Aquaculture production is not profitable. We have $F^P/M^P = [r_F/(\alpha_F P)][1-1/(\alpha_F P K_F)]/[L-(r_F/\alpha_F)(1-1/(\alpha_F P K_F))]$. Notice the assumption, which manufacturing always exists, guarantees that the denominator is positive.

For $P = a_{LA}, W = 1 = \alpha_F S_F P = P/a_{LA}$. Aquaculture, the capture fishery and manufacturing coexist. Notice that the relative supply F^P/M^P must be greater than or equal to $[r_F/(\alpha_F a_{LA})][1-1/(\alpha_F a_{LA} K_F)]/[L-(r_F/\alpha_F)(1-1/(\alpha_F a_{LA} K_F))]$, where fish is produced by the capture fishery alone at the relative price $P = a_{LA}$. The relative supply F^P/M^P could approach infinity when workers keep switching from manufacturing to aquaculture. Δ

Proof: Proposition 7

In (31), an increase in α_A or θ_A shifts down the AC/W curve. The unit labor requirement in aquaculture a_{LA} decreases because it equals the minimum of AC/W. When aquaculture, the capture fishery and manufacturing coexist, the fish price P^* equal the unit labor requirement in aquaculture a_{LA}. Thus, P^* decreases too.Δ

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