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Externalities and foreign capital in aquaculture production in developing countries

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Abstract: Most developing countries are increasingly dependent on fresh water based aquaculture (cage culture) to supplement the declining catch from capture fisheries. Yet, the competition for space between capture fisheries and cage culture, pollution generated by cage culture, and fish markets interaction effects have yet to be clearly conceptualized in a bioeconomic framework. Furthermore, the economic viability of cage culture depends on substantial investment thresholds, engendering foreign direct investment in the industry in developing countries. This paper develops a conceptual model for fresh water based aquaculture that account for (i) space allocation, pollution, and interaction of markets for fish; and (ii) foreign capital financing aquaculture production. We found that a Pigouvian tax (optimum ad valorem tax) that corrects the externalities depends on economic and biological parameters in aquaculture and capture fisheries. Correcting for the externalities results in a reduction in aquaculture production but not optimum wild catch. Furthermore, if the aquaculture is financed with foreign capital, then the Pigouvian tax equals the ratio of net to total benefit from aquaculture. Numerical values are used to illustrate the results.

Keywords: aquaculture, externalities, Pigouvian tax, ad valorem tax

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1 Introduction

Over the past 30 years, aquaculture fish production has increased sharply and has continued to expand around the world because of the dwindling catches of capture fisheries coupled with increased appetite for fish protein (FAO 2008). With the exception of salmon farming in Norway, aquaculture production has stagnated over the past three decades in the developed world (FAO 2012). As a result, developing countries (especially China) have been responsible for over 90 per cent of the growth in global fish production. It has been noted that aquaculture, through supplying fish and other aquatic products rich in protein, essential fatty acids, vitamins, and minerals, could contribute to eliminating hunger and malnutrition (FAO 2006). In addition, the sector could provide employment opportunities and contribute significantly to improving incomes and economic development in developing countries (FAO 2006).

In spite of being bedevilled with malnutrition, Sub-Saharan Africa (SSA) in particular has not made a meaningful contribution to the growth in aquaculture over the last three decades. Its contribution to world aquaculture production is estimated at less than 1 per cent, and per capita fish consumption within the region is the lowest (barely 9.1 kg per capita by 2009) (FAO 2012; Hecht 2006). The contributing factors to the low output include inadequate domestics and foreign investment in the sector (Leung et al. 2007).[1] Fish, however, remains extremely important in the African diet, making up 17.4 per cent of the protein intake (Brummett et al. 2008). For the region to meet its growing demand for fish protein, aquaculture has to develop to an annual average of at least 8.3 per cent—a figure that is significantly higher than current levels (Muir et al. 2005).

Statistics available from the United Nation's Food and Agriculture Organization (FAO 2010) shows aquaculture production increased five-fold between 1998 and 2008 because of a number of critical regional projects within SSA and initiatives that increased private investment in the sector. The rise in freshwater fish production between 2002 and 2012 resulted in an increase in Africa's contribution to global aquaculture production from 1.2 to 2.2 per cent (FAO 2012).[2] With regard to employment, the number of people engaged in the industry in Africa has been increasing by 5.9 per cent annually, which is the highest among all other regions (FAO 2012). It is estimated that about 43 per cent of the continent has the potential for farming tilapia (Hishamunda 2007).

Notwithstanding the benefits from aquaculture (especially freshwater fish production) in African countries, its expansion could generate some negative externalities. First, nitrogen released from feeds and fish wastes could lead to nutrient over-enrichment and eutrophication in the entire management area if the aquaculture involves water-based systems (i.e. pen or cage culture) (see e.g. EJF 2003; FAO 2008; Krause et al. 2015; Wiber et al. 2012). Second, it is possible for diseases to be spread from cultured fish to the wild stock, thereby reducing population of the wild stocks. Third, the biological fitness of the wild stock could alter if genetically different species escape from pens and cages. Furthermore, large pens and cages could occupy potential artisanal fishing grounds. Finally, in small economies like countries in SSA, the demand function for fish is downwards sloping indicating that harvest from aquaculture could impact revenue and profitability of wild fish catches.

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[1] The other factors are inadequate feed, lack of extension services, poor market access, ill-defined user rights, and poor legal and institutional frameworks.

[2] Freshwater fish farming makes up over 99 per cent of aquaculture in Africa (FAO 2012).

In a recent work, Hoagland et al. (2003) model ocean space allocation problem for aquaculture production without addressing pollution externality from aquaculture and market interaction effects. Moreover, the study did not explicitly derive Pigouvian tax (corrective tax) that is necessary to internalize the environmental opportunity cost. These extensions are considered in this study. It is noteworthy that pens and cages are normally located offshore in natural bodies of water and require sizeable investment which is not affordable to most farmers in SSA. In addition, although fish farming can be done at small- to large-scale levels, artisanal aquaculture fish production is rarely profitable (Brummett et al. 2008). According to the FAO (2006), for the coming years and decades, Africa (especially SSA) should be a high priority region for aquaculture development and fish production must become an important part of the overall development process for the continent. To realize this objective more emphasis is put on foreign direct investment (FDI) in aquaculture within the region. As noted by Hishamunda (2007), aquaculture in Africa can only be developed if commercial aquaculture is promoted. As a result, a number of countries in Africa, including Ghana, are making efforts at attracting FDI to the sector from countries like Brazil, China, Chile, France, and the United Kingdom (Hishamunda 2007). To the best of our knowledge, no research exists to determine the optimum ad valorem tax to be imposed on foreign investment in aquaculture; hence, this study fills this gap as well. The results from our model are empirically illustrated.

The results indicate that both biological and economic parameters determine the Pigouvian tax (optimum ad valorem tax) that corrects the externalities (competition for space, market interaction, and pollution). As a tax that accounts for competition for space and fish market interactions decreases aquaculture production, wild fish catch increases at the optimum. Furthermore, if the capital for the aquaculture is from FDI, the expression for the Pigouvian tax is the ratio of net to total benefit from aquaculture. The simulated results show that, for capture fisheries, irrespective of the source of the capital for aquaculture, the Pigouvian tax should be decreasing in intrinsic growth rate, pollution from aquaculture, and the cost of farming fish. On the other hand, for aquaculture operators, irrespective of the source of capital, the tax should increase in intrinsic growth rate of the capture fish stock and pollution but decrease in the cost of farming fish.

The remainder of the paper is organized as follows. Section 2 contains the theoretical model of aquaculture externalities and derived expression for the Pigouvian tax. Section 3 presents an extended model that accounts for foreign investment in aquaculture. Section 4 presents the conclusions.

2 The analytical framework of aquaculture externalities

The modelling strategy is as follows. Simple bio-economic models of the capture fisheries manager's problem and the aquaculture farmer's problem are presented. This is followed by a combined model for the social planner to investigate the congestion and pollution externalities. Furthermore, as aquaculture investments in a number of developing countries are predominantly financed by FDI, we sought an optimum tax on revenue that internalizes the externalities. These models are presented in turns.[3]

[3] All notations are explained in Appendix Table A1.

2.1 The capture fisheries manager's problem

Assume that the capture fishery is managed independently. Suppose the manager of an artisanal inland fishery decides on catch biomass (h), which is traded in an imperfect competitive market with a downward sloping demand curve. Let the price per unit (e.g. kilogram) of the catch depend on the wild catch, h, and harvest from aquaculture (z)—that is, $p(h,z)$. In addition, assume the cost per unit harvest is $c(x)$, where $c_x(x)<0$, $c_{xx}(x)>0$, and x is the capture fish stock. If future costs and benefits are discounted at the rate $\delta(>0)$, then the present value of discounted stream of surpluses from the capture fishery is:

$$A(h,x;z)=\int_0^{\infty}\left(p(h,z)-c(x)\right)he^{-\delta t}dt. \tag{1}$$

Let the rate of growth function of the wild stock be $g(x,k)$, where $g_x(\bullet)<0$, $g_k(\bullet)>0$, $g_{xx}(\bullet)\leq 0$, $g_{kk}(\bullet)\geq 0$, $g_{xk}(\bullet)\geq 0$, and k is environmental carrying capacity. Cage culture takes away potential fishing areas (decreases wild fish stock) and thereby increases the cost per unit harvest of capture fish. Following Hoagland et al. (2003), let the remainder of the carrying capacity—if cage culture takes away part of the carrying capacity—be $k=k(m)=k_0-\omega m$, where k_0 is the initial carrying capacity, m is the lake area devoted to aquaculture and ω is a constant conversion factor of cage size to carrying capacity. The time derivative of the total biomass (i.e. $\dot{x}$) increases in the growth of the stock but decreases in human predation (catch). Thus, the stock dynamic equation is:

$$\dot{x}=g(x,k(m))-h. \tag{2}$$

The representative fisher's objective is to maximize Equation (1), with respect to catch, subject to the stock evolution (i.e. Equation (2)).

The corresponding current value Hamiltonian can be specified as:

$$H(h,x,k(m);z)=\left[p(h,z)-c(x)\right]h+\lambda\left(g(x,k(m))-h\right), \tag{3}$$

where λ is the scarcity value of the capture fish stock or the marginal value assigned by the planner to the marginal reductions in the fish stock. The maximum principle provides the following first-order condition with respect to the flow variable, catch (h):

$$\frac{\partial H(\cdot)}{\partial h}=p_h(h,z)h+p(h,z)-c(x)-\lambda=0\Rightarrow p_h(h,z)h+p(h,z)-c(x)=\lambda. \tag{4}$$

From Equation (4), to maximize inter-temporal benefit from the fishery, the net marginal benefit, $(p_h(h,z)h+p(h,z)-c(x))$, must equal to the scarcity value of the stock (λ). Clearly, the net marginal surplus depends on the catch, capture fish stock, and biomass production from the aquaculture. The co-state equation corresponding to Equation (3) is:

$$\dot{\lambda}-\delta\lambda=-\lambda g_x+c_x(\cdot)h. \tag{5}$$

Equation (5) stipulates that in dynamic equilibrium, returns on investing the proceeds from harvesting a kilogram of fish ($\delta\lambda$) must equate to the opportunity cost of catching the fish, which includes capital gain ($\dot{\lambda}$) and some stock effect ($\lambda g_x - c_x(.)h$)). In steady state, there is no gain in fish stock and the shadow price (i.e. $\dot{x} = \dot{\lambda} = 0$); hence, Equations (2) and (5) give us $g(x,k)=h$ and $\lambda=(-c_x(.)h)/(\delta-g_x)$, respectively. Assume that the aquaculture production depends on the cage size, so that the production function is $z=z(m)$. Using this expression and substituting the above values for h and λ in Equation (4), we have:

$$p_h\big(g(x,k(m)),z(m)\big)g(x,k(m))\big)+p\big(g(x,k(m)),z(m)\big)-c(x)=\frac{-c_x(\cdot)g(x,k(m))}{\delta-g_x(x,k(m))}. \quad (6)$$

Equation (6), which is a reaction function, could potentially be solved for the equilibrium values of the capture fish stock as a function of the size of the area devoted to aquaculture (i.e. $\dot{x} = x(m)$), if the specific forms of the relevant functions are known.

2.2 The aquaculture farmer's problem

As indicated earlier, in recent times, policy makers in several African countries have been making conscious efforts at encouraging investment in aquaculture to ease the pressure on capture fish stocks, which are already overcapitalized and overexploited. So far, the response has been encouraging. Suppose the recurrent operation cost of the aquaculture is a function of the size of the cage (i.e. $\varsigma(m)$) and the cost of an extra unit (v) of the cage area is given by the function $\tau(v)$, with $\tau_v(v)>0$. Then, the corresponding present value of the net benefit from the aquaculture is:

$$B(z;m,h)=\int_0^{\infty}\big(p(h,z(m))z(m)-\varsigma(m)-\tau(v)\big)e^{-\delta t}dt. \quad (7)$$

Let the equation of motion that defines the change of the cage area over time be:

$$\frac{dm}{dt}\left(=\dot{m}\right)=v. \quad (8)$$

The current value Hamiltonian corresponding to Equations (7) and (8) is:

$$H(v;m,h)=p(h,z(m))z(m)-\varsigma(m)-\tau(v)+\mu\cdot v, \quad (9)$$

where μ is the shadow value of the cage area. The maximum principle generates the following first-order condition with respect to the flow variable v:

$$\frac{\partial H(\bullet)}{\partial v}=0 \Rightarrow -\tau_v+\mu=0 \Rightarrow \tau_v=\mu. \quad (10)$$

In inter-temporal equilibrium, the farmer will expand the cage marginally if the marginal benefit of the expansion (i.e. measured by the shadow value of the total cage area, μ) is at least equal to the marginal cost of the expansion (i.e. τ_v). The co-state equation defining the dynamic equilibrium is:

$$\dot{\mu} - \delta\mu = \varsigma_m(m) - \left[p_z(h, z(m))z(m) + p(h, z(m))\right]z_m(m). \tag{11}$$

Similarly, from Equation (11), in a dynamic equilibrium, the capital gain from investing in an extra unit of the cage area ($\dot{\mu}$) plus the marginal benefit from fish harvest attributable to the marginal increment in the cage area (i.e. $[p_z(h,z(m)z(m)+p(h,z(m))]z_m(m)-\varsigma_m(m))$ should balance the marginal opportunity of interest earnable on μ (i.e. $\delta\mu$). In steady state, we have $\dot{\mu} = \dot{\mu} = \nu = 0$. Combining Equations (10) and (11) and using $h=g(x,k(m))$, we get the following equation:

$$\varsigma_m(m) = \left[p_z(g(x,k(m)), z(m))z(m) + p(g(x,k(m)), z(m))\right]z_m(m) - \delta\tau_\nu. \tag{12}$$

Again, Equation (12), which is a reaction function, could be solved for the equilibrium level of m as a function of the wild fish stock (i.e. $m^*=m(x)$). The two reaction functions (i.e. Equations (6) and (12)) could be solved simultaneously to obtain the equilibrium values of m^* and x^*. It is important to note that these values are suboptimal because they do not account for the congestion (interaction) and pollution externalities.

2.3 Functional forms for numerical stimulations

To obtain numerical solutions, we assume the following specific functional forms: a logistic growth function for the capture stock (i.e. $g(x,k(m))=rx[1-(x)/(k_0-\omega m)]$, where r is the intrinsic growth rate; a Schaefer cost function $c(x)=c/(\sigma x)$, where c is cost per unit effort, and σ is catchability coefficient; a downward slopping linear demand function, $p(h,z)=a-b(h+z)$, where $a,b>0$; a non-linear aquaculture production function of the form $z(m)=\theta m^{\varepsilon}$, following Welcomme (1995); a linear cost function for acquiring an extra unit of the management area $\tau(\nu)=\nu\tau$, assumed for tractability; and a linear fish production function, $\varsigma(m)= \varsigma m$, also assumed for computational convenience, but without loss of generality.

Furthermore, to derive the numerical results, some values were assumed. As the dominant species is tilapia, an intrinsic growth rate of 1.358 was used (Romana-Eguia et al. 2010). Lake Volta has the second largest tilapia farm in Africa, with a carrying capacity of 80,000 metric tons (Vanderpuye 1984). As a result, we assume the figure constitutes the carrying capacity in the growth function. Following Akpalu and Bitew (2011), a social discount rate of 5 per cent was used. The remainder of the parameter values was chosen for convenience. Tables 1–3 show the numerical values used for the analysis.

2.4 Numerical results: non-cooperative solutions

From Table 1, a higher intrinsic growth rate of the capture fish stock, which could depend on say species composition, increases the equilibrium capture fish stock and the catch while dampening aquaculture production. Furthermore, aquaculture production declines but optimal catch of capture fisheries increases if the cost of farming fish increases. The results are intuitive as increased cost of aquaculture production is expected to decrease production but increase capture fisheries to make up for the shortfall. It is worth noting, however, that these equilibrium values for catch, stock levels, and aquaculture production are suboptimal because congestion and pollution externalities are not accounted for.

Table 1: Parameters used for numerical simulations and corresponding optimum values

Parameters and variables	Baseline parameter values	Change in r	Change in ς
c	10	10	10
δ	0.05	0.05	0.05
σ	0.016	0.016	0.016
τ	1	1	1
a; b	44; 0.00025	44; 0.00025	44; 0.00025
θ;ε	10; 0.5	10; 0.5	10; 0.5
ω	0.1	0.1	0.1
ς	50	50	**54.38**
r	1.358	**1.79**	1.358
k_0	80,000	80,000	80,000
Fish stock (x^*)	38,537.60	38,894.7	38,537.7
Catch (h^*)	27,123.26	35,772.1	27,123.65
Aquaculture (z^*)	37.16	35.00	34.17
Cage size (m^*)	13.81	12.25	11.68
$p^*=[a-b(h^*+z^*)]$	37.2099	35.0482	37.2105

Source: Authors' compilation. Bold text indicates a new parameter value.

2.5 The overall social planner's problem

Now suppose an overall social planner exits, and his/her objective is to maximize total surplus from both fisheries. Cage culture imposes negative externality on the environmental carrying capacity of the remaining capture fisheries area as a result of the use of chemicals. Assume the pollution from the cage culture depends on the size of the cage (i.e. γm, where γ is a constant) so that the *instantaneous* carrying capacity becomes $k=k_0-(\omega+\gamma)m$. The objective of the planner is to maximize Equation (13) (i.e. net benefits from aquaculture and capture fisheries), with respect to catch and extra unit of the lake converted to aquaculture.

$$V(h,z;x,m)=A(h;x,m)+B(z,m,h). \tag{13}$$

The constraints to the objective function are the dynamic equations (i.e. Equations (2) and (8)) as well as the carrying capacity constraint. The corresponding current value Hamiltonian is:

$$\begin{aligned}H(\cdot)=&\big(p(h,z(m))-c(x)\big)h+p(h,z(m))z(m)-\varsigma(m)\\&-\tau(\nu)+\lambda_s\big(g(x,k(m))-h\big)+\mu_s\nu\end{aligned}. \tag{14}$$

The maximum principle generates the following first-order conditions:

$$\frac{\partial H}{\partial h}=0\Rightarrow p_h\big(h,z(m)\big)\big(h+z(m)\big)+p\big(h,z(m)\big)-c(x)=\lambda_s, \tag{15}$$

$$\frac{\partial H}{\partial \nu}=0\Rightarrow \tau_\nu=\mu_s. \tag{16}$$

Equation (15) differs from Equation (4) by $p_h(h,z(m))z(m)<0$ indicating that, in inter-temporal equilibrium, the socially optimum catch level is lower than the 'private' equilibrium catch level of the capture fisheries manager. Consequently, decentralizing the two subsectors could result in over-harvesting of the capture fish stock. We refer to this as the congestion externality effect. The corresponding co-state equations (for the co-state variables x and m, respectively) are:

$$\dot{\lambda}_s - \delta\lambda_s = -\lambda_s g_x(\cdot) + c_x(x)h \tag{17}$$

and

$$\begin{aligned}\dot{\mu}_s - \delta\mu_s = \varsigma_m(m) - \left[p_z(h,z(m))z(m) + p(h,z(m))\right]z_m(m) \\ -p_z(h,z(m))z_m(m)h - \lambda_s g_k(\cdot)k_m(\cdot)\end{aligned}. \tag{18}$$

Whereas Equations (5) and (17) are the same, Equations (11) and (18) are obviously different. As $p_z(h,z(m)z_m(m)h<0$ and $\lambda_s g_k(.)k_m(.)=-\omega\lambda_s g_k(.)-\lambda_s g_k(.)<0$, in dynamic equilibrium, the net benefit from marginally expanding the cage is overstated favouring increasing the cage size in Equation (11). Thus, properly accounting for the resource use externality (pollution) discourages expansion of aquaculture.

In steady state $\dot{m} = \dot{x} = \dot{\lambda}_s = \dot{\mu}_s = v = 0$ and $h=g(x,k_0-m(\omega+\gamma))$; hence, the tax expression becomes:

$$\eta = \gamma\left[p_h(g(\cdot),z(m))(g(\cdot)+z(m)) + p(g(\cdot),z(m)) - c(x)\right]g_k(\cdot). \tag{19}$$

Also, we have the following expressions for the shadow values:

$$\lambda_s = -\frac{c_x(\cdot)g(\cdot)}{\delta - g_x(\cdot)}, \tag{20}$$

$$\mu_s = \frac{\left[p_z(g(\cdot),z(m))(g(\cdot)+z(m)) + p(g(\cdot),z(m))\right]z_m(m) - \left(\frac{c_x(\cdot)g(\cdot)}{\delta - g_x(\cdot)}\right)g_k(\cdot)k_m(\cdot) - \varsigma_m(m)}{\delta}. \tag{21}$$

Substituting these values in Equations (17) and (18), the equations that relate the optimum stock and cage size become:

$$p_h(g(\cdot),z(m))(g(\cdot)+z(m)) + p(g(\cdot),z(m)) - c(x) = -\frac{c_x(\cdot)g(\cdot)}{\delta - g_x(\cdot)}, \tag{22}$$

$$\begin{aligned}\delta\tau_v = \left[p_z(g(\cdot),z(m))(g(\cdot)+z(m)) + p(g(\cdot),z(m))\right] \\ z_m(m) - \left(\frac{c_x(\cdot)g(\cdot)}{\delta - g_x(\cdot)}\right)g_k(\cdot)k_m(\cdot) - \varsigma_m(m)\end{aligned}. \tag{23}$$

Equations (22) and (23) could be solved simultaneously for the socially optimum stock, cage size, and aquaculture fish production.

The first-order conditions and the co-state equations of the social planner are different from those of the capture fisher and the fish farmer owing to congestion externality and pollution externality effects. Congestion externality relates to the competition for the carrying capacity (lake space effect) and price effect due to imperfect competition in the fish market. Comparing Equations (4) and (15), we obtain the following tax expression:[4]

$$A_c = -P_h(\cdot)z(m), \tag{24}$$

Equation (24) indicates that the tax (A_c) on the capture fishery should correct for the externality owing to the market interaction effect as a result of competition in the fish market ($-P_h(.)z(m)$). Also, comparing Equations (11) and (18), the following expression is obtained for the tax for the fish farmer:

$$A_a z_m(m) = -P_z(\cdot)z_m(m)g(\cdot) - \lambda_s g_k(\cdot)k_m(m) \Rightarrow A_a = \frac{-p_z(\cdot)z_m(m)g(\cdot) + g_k(\cdot)k_m(m)\left(\dfrac{c_x(\cdot)g(\cdot)}{\delta - g_x(\cdot)}\right)}{z_m(m)}, \tag{25}$$

where $k_m = -\omega$ as $k = k_0 - \omega m$ (no pollution externality). Again, from Equation (25), the tax must correct for the market interaction effect ($-P_z(.)h$) and some capture fish biomass growth effect of increased cage size ($-\lambda_s g_k(.)k_m(m)(z_m(m))^{-1}$)). Furthermore, if we have pollution externality due to aquaculture so that the carrying capacity is explicitly define as $k = k_0 - (\omega + \gamma)m$, pollution tax can be defined as:

$$A_p = \frac{-\gamma\left(\dfrac{c_x(\cdot)g(\cdot)}{\delta - g_x(\cdot)}\right)g_k(\cdot)}{z_m(m)}. \tag{26}$$

Equation (26) indicates that the pollution tax is the ratio of value of the marginal damage to the carrying capacity—due to the pollution (i.e. $-\gamma([c_x(.)g(.)]/[\delta - g_x(.)])g_k(.)$)—to the marginal gain as a result of expanding the cage area (i.e. $z_m(m)$) .

2.6 Numerical results: social optimum outcomes

Using the specific functions and the numerical values, the optimum values reported in Table 2 are obtained. The results clearly show that the optimum wild catch is higher but aquaculture production is lower than their corresponding non-cooperative values. The lower aquaculture production is due to internalization of the carrying capacity effect. Interestingly, although the capture fisheries are taxed to address the market interaction effect, its optimum catch increases because of increased carrying capacity as less area is made available for aquaculture. The overall

[4] Note that we assume a price-based tax so that the net after tax to the capture fisher and the fish farmer are $(p(.) - A_c)h$ and $(p(.) - A_a)z(m)$, respectively.

net effect is lower aggregate catch, which leads to an increase in the price of fish. Furthermore, the presence of pollution lowers optimum wild fish catch and aquaculture production of fish. However, it brings about an additional tax on the fish farmers, increasing the congestion externality and carrying capacity effect tax on the fish farmer, but reducing the congestion tax on the capture fisher.

Table 2: Optimum wild fish catch and aquaculture harvest if local capital finances aquaculture and externalities are internalized

Parameters and variables	Baseline parameter values (no pollution)	Change in r	Change in ς	Baseline parameter values (with pollution)
c	10	10	10	10
δ	0.05	0.05	0.05	0.05
σ	0.016	0.016	0.016	0.016
τ	1	1	1	1
a; b	44; 0.00025	44; 0.00025	44; 0.00025	44; 0.00025
θ,ε	10; 0.5	10; 0.5	10; 0.5	10; 0.5
ω	0.1	0.1	0.1	0.1
ς	50	50	**54.38**	50
r	1.358	**1.790**	1.358	1.358
k_0	80,000	80,000	80,000	80,000
γ	0	0	0	**0.1**
Fish stock (x*)	38,537.87	38,895.026	38,537.939	38,537.477
Catch (h*)	27,123.43	35,772.4	27,123.5	27,123.40
Aquaculture (z*)	29.822	25.5124	27.4648	29.2725
Cage size (m*)	8.89352	6.5088	7.5431	8.5688
Capture fisher tax (A_c*)	0.0075	0.00637	0.00686	0.00731
Aquaculture tax (A_a*)	7.3524	9.5062	7.30725	7.9028
Externality tax (A_p*)	0.0000	0.0000	0.0000	14.0254
$p^*=[a-b(h^*+z^*)]$	37.2117	35.0505	37.2123	37.2118
$(A_c^*/p^*)\times100$	0.02003	0.01819	0.01845	0.01967
$(A_a^*/p^*)\times100$	19.7583	27.1216	19.6367	21.2374
$(A_p^*/p^*)\times100$	0.0000	0.0000	0.0000	37.6908

Source: Authors' compilation. Bold text indicates a new parameter value.

Finally, with regard to the price-based tax on aquaculture, the optimum rate should increase if the intrinsic growth rate of the capture fish stock increases or if the marginal cost of farming fish increases. Thus, aquaculture should be discouraged if it is less profitable, because the capital from the domestic economy has opportunity cost.

3 Modelling foreign capital in aquaculture

Now suppose the capital for setting up the aquaculture comes from FDI. A feasible policy option will be to impose ad valorem tax that maximizes economic surplus from both fisheries. Let the tax be α. The social planner's problem is to maximize the following function:

$$V(x,h,m)=\int^{\infty}V(x,h,m)=\int_0^{\infty}\left(\alpha p(h,z(m))z(m)+\left(p(h,z(m))-c(x)\right)h\right)e^{-\delta t}dt. \tag{27}$$

The constraints are the two equations of motion (i.e. Equations (2) and (8)) and an additional constraint of an isoperimetric form (see Akpalu and Parks 2007), that is,

$$\int_0^{\infty}\left((1-\alpha)\,p(h,z(m))z(m)-\varsigma(m)-\tau(\nu)\right)e^{-\delta t}dt\geq0. \tag{28}$$

Equation (28) stipulates that the stream of net benefits that accrue to the provider of the FDI must be non-negative. The corresponding Lagrangian function is:

$$L = H(\cdot) + \psi\left\langle (1-\alpha)\, p\big(h, z(m)\big) z(m) - \varsigma(m) - \tau(\nu) \right\rangle, \tag{29}$$

where ψ is a Lagrange multiplier, and $H(.) = \alpha p(h, z(m)) z(m) + (p(h, z(m)) - c(x))h + \lambda_s(g(x, k(m)) - h) + \mu\nu$.

The first-order conditions with respect to the flow variables, following the maximum principle, are:

$$\frac{\partial L}{\partial \alpha} = 0 \Rightarrow p\big(h, z(m)\big) z(m) - \psi p\big(h, z(m)\big) z(m) = 0 \Rightarrow \psi = 1, \tag{30}$$

$$\begin{aligned} \frac{\partial L(\cdot)}{\partial h} = 0 \Rightarrow \alpha p_h\big(h, z(m)\big) z(m) + p_h\big(h, z(m)\big) h + p\big(h, z(m)\big) \\ + \psi(1-\alpha)\, p_h\big(h, z(m)\big) z(m) - c(x) = \lambda_s \end{aligned}, \tag{31}$$

$$p_h\big(h, z(m)\big)\big(h + z(m)\big) + p\big(h, z(m)\big) - c(x) = \lambda_s, \tag{32}$$

$$\frac{\partial L}{\partial \nu} = 0 : \tau_\nu = \mu. \tag{33}$$

And the co-state equations are:

$$\dot{\lambda}_s - \delta\lambda_s = -\lambda_s g_x + c_x(x) h, \tag{34}$$

$$\begin{aligned} \dot{\mu}_s - \delta\mu_s = -\alpha\big[p_z(\cdot) z_m(m) z(m) + p(\cdot) z_m\big] - p_z z_m h - \lambda_s g_k(\cdot) k_m(\cdot) \\ + \psi\varsigma_m(m) - \psi(1-\alpha)\big[p_z(\cdot) z_m(m) z(m) + p(\cdot) z_m\big] \end{aligned}. \tag{35}$$

Again, in steady state, $\dot{m} = \dot{x} = \dot{\lambda}_s = \dot{\mu}_s = \nu = 0$ implies:

$$p_h\big(g(\cdot), z(m)\big)\big[g(\cdot) + z(m)\big] + p\big(g(\cdot), z(m)\big) - c(x) = -\left(\frac{c_x(x) g(\cdot)}{\delta - g_x(\cdot)}\right), \tag{36}$$

$$\delta\tau_\nu = p_z(\cdot) z_m(m)\big[z(m) + g(\cdot)\big] + p(\cdot) z_m - \left(\frac{c_x(x) g(\cdot)}{\delta - g_x(\cdot)}\right) g_k(\cdot) k_m(\cdot) - \varsigma_m(m). \tag{37}$$

In addition to the first-order conditions, we have the following transversality condition:

$$\frac{\partial L}{\partial \psi} = (1-\alpha)\, p\big(h, z(m)\big) z(m) - \varsigma(m) - \tau(\nu) \geq 0, \quad \psi \geq 0, \quad L_\psi \psi = 0. \tag{38}$$

Since ψ=1, it follows that $\partial L/\partial\psi$=0, and the optimum tax expression is:

$$\alpha^* = 1 - \left(\frac{\varsigma(m) + \tau(v)}{p(z(m), h) z(m)} \right). \tag{39}$$

Equation (38) stipulates that, in steady state, the ad valorem tax on aquaculture must be the ratio of the net revenue to total revenue from the aquaculture. Equations (36), (37), and (39) may be solved simultaneously for x^*, m^*, and α^*.

To obtain the expression for the price-based congestion externality tax (to be paid by the capture fisher), under foreign capital in aquaculture, we compare Equations (4) and (31), which gives:

$$A_{c(FDI)} = -P_h(\cdot) z(m). \tag{40}$$

The congestion externality tax expression for the capture fishers, when aquaculture is financed by FDI, is similar to the case where fish farming is locally funded. Similarly, using the specific functional forms and the numerical values, the optimum values of the state and control variables as well as the taxes are reported in Table 3.

3.1 Numerical results for FDI: The social optimum outcomes

The results from Table 3 indicate that the ad valorem tax on aquaculture should increase if pollution from its activities intensifies or the intrinsic growth rate of the capture fish stock increases. Thus, higher intrinsic growth rate implies capture fisheries should be favoured over aquaculture, and hence the higher tax rate. On the other hand, the optimum tax rate should be set lower if the cost of farming fish increases. Notably, there is no difference between the characteristics of the tax in a situation where capital for aquaculture comes from the domestic economy and the case where FDI finances aquaculture. In both cases, the optimum tax rate is reduced if the cost of farming fish increases. This is in spite of domestic capital having opportunity cost within the economy.

Table 3: Optimum wild fish catch and aquaculture harvest if foreign capital finances aquaculture and externalities are internalized

Parameters and variables	Baseline parameter values (no pollution)	Change in r	Change in ς	Baseline parameter values (with pollution)
c	10	10	10	10
δ	0.05	0.05	0.05	0.05
σ	0.016	0.016	0.016	0.016
τ	1	1	1	1
a; b	44; 0.00025	44; 0.00025	44; 0.00025	44; 0.00025
θ;ε	10; 0.5	10;0.5	10; 0.5	10; 0.5
ω	0.1	0.1	0.1	0.1
ς	50	50	**54.38**	50
r	1.358	**1.79**	1.358	1.358
k_0	80,000	80,000	80,000	80,000
γ	0	0.0	0.0	**0.1**
Fish stock (x^*)	38,537.8744	38,895.0	38,537.939 0	38,537.5
Catch (h^*)	27,123.4	35,772.4	27,123.5	27,123.2
Cage size (m^*)	8.8935	6.5088	7.5431	8.5688
Ad valorem tax on price (α^*)	0.5993	0.6361	0.5986	0.6067
Capture fisher tax (A_{cFDI}^*)	0.0075	0.0064	0.0069	0.0073
$p^*=[a-b(h^*+z^*)]$	37.2117	35.0505	37.2123	37.2119
$(A_{cFDI}^*/p^*)\times 100$	0.0200	0.0182	0.0185	0.0197

Source: Authors' compilation. Bold text indicates a new parameter value.

4 Conclusion

Owing to increasing over-exploitation of capture fish stocks, developing countries have embarked on policies to promote aquaculture to meet their minimum fish protein requirements. Typically, cage culture interacts with capture fisheries in a number of ways. These include the pollution of capture fisheries by cage culture, the interaction of markets for wild catch and harvest from aquaculture, and competition for space between the two fisheries. In addition, capital for aquaculture in developing countries mostly comes from FDI. The goal of public policies, therefore, is to design instruments capable of internalizing these externalities, as well as ensuring that the resource-rich countries obtain a fair share of the return from cage culture from foreign investors. The simple bio-economic model used in this paper suggests pathways to achieving these objectives.

The results from the optimization programmes indicate that the inter-temporal extraction level is lower for the fish farmer but higher for the capture fisher than optimally desired. The reason for this is that taxes on aquaculture results in a reduction in cage area, which then leads to an increase in wild fish catch in spite of the tax for the market interaction effect (imperfect competition in the fish market). Thus, a tax on both fishers aimed at internalizing the market interaction effect (congestion externality), which causes over-harvesting only leads to a reduction in aquaculture production levels. In addition, the fish farmer must be taxed for the impact of the increased cage size on capture fish biomass growth as well as the negative externality resulting from chemical usage. The proposed tax is an ad valorem tax, which is easier to implement in developing countries.

The optimum tax rate has been found to be responsive to changes in intrinsic growth rate of the capture fish stock, the cost of farming the fish, and the initial carrying capacity of the wild fish stock. Furthermore, if aquaculture is financed by FDI, the optimum price-based tax on the fish farmer is simply the share of profit in total revenue. Thus, an increase in the cost of farming fish must be accompanied by a reduction in the tax rate, irrespective of where the capital for farming fish is coming from.

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Appendix

Table A1: Nomenclatures

Parameter and variable definitions	Parameters and variable
Cost per unit effort	c
Social discount rate	δ
Catchability coefficient	σ
Price per unit (e.g. square meter) of cage area	τ
Demand function parameters	a; b
Aquaculture production parameter	θ; ε
Intrinsic growth rate	r
Environmental carrying capacity	k_0
Marginal cost of farming fish	ς
Marginal reduction in environmental carrying capacity due to expansion of aquaculture	ω
Capture fish stock (e.g. in biomass; i.e. tons of fish in the aquatic environment)	x
Wild fish catch (in biomass)	h
Aquaculture harvest (in biomass)	z
Cage size (e.g. cubic metres)	m
Ad valorem tax (on foreign investor)	α
Extra unit of fishing area used for cag	ν

Source: Authors' compilation.