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Optimal Allocation of Anchovy Stocks as Baitfish for Tuna and Food for Local Communities in Developing Coastal Countries

Wisdom Akpalu

Central America
Research Program in Economics and Environment for Development in Central America Tropical Agricultural Research and Higher Education Center (CATIE)

Chile
Research Nucleus on Environmental and Natural Resource Economics (NENRE)
Universidad de Concepción

China
Environmental Economics Program in China (EEPC)
Peking University

Colombia
The Research Group on Environmental, Natural Resource and Applied Economics Studies (REES-CEDE), Universidad de los Andes, Colombia

Ethiopia
Environment and Climate Research Center (ECRC), Policy Studies Institute, Addis Ababa, Ethiopia

Ghana
The Environment and Natural Resource Research Unit, Institute of Statistical, Social and Economic Research, University of Ghana, Accra

India
Centre for Research on the Economics of Climate, Food, Energy, and Environment, (CECFEE), at Indian Statistical Institute, New Delhi, India

Kenya
School of Economics
University of Nairobi

Nigeria
Resource and Environmental Policy Research Centre, University of Nigeria, Nsukka

South Africa
Environmental Economics Policy Research Unit (EPRU)
University of Cape Town

Sweden
Environmental Economics Unit
University of Gothenburg

Tanzania
Environment for Development Tanzania
University of Dar es Salaam

Uganda
EfD-Mak, School of Economics and Department of Agribusiness and Natural Resource Economics, Makerere University, Kampala

USA (Washington, DC)
Resources for the Future (RFF)

Vietnam
University of Economics
Ho Chi Minh City, Vietnam

Contents

1. Introduction.. 1

2. The Tuna Fishing Industry in Ghana 2

3. The Theoretical Model 4

3.1 The Cooperative Outcome: The Social Planner's Program 4

3.2 Non-Cooperative Outcomes... 7

3.3 The Anchovy Fleet.. 7

3.4 The Tuna Fleet 8

3.5 The Economic Policy Instrument.. 9

3.6 The Use of Destructive Baitfish Fishing Methods.. 10

3.7 The Foreign Tuna Fleet: Social Planner's Problem 11

3.8 Instantaneous Harvest Function of Tuna Fishers... 13

4. Numerical Illustration of the Results 14

4.1 The Sustainable Yield Functions 14

4.2 The Data and Numerical Illustrations 15

4.3 The Sustainable Yield Regression Results 15

4.4 Numerical Simulations 17

4.4.1 Local Tuna Fleet Ownership and Cooperative Solution.................................... 17

4.5 Local Tuna Fleet Ownership and Non-Cooperative Solutions 18

4.6 Foreign Tuna Fleet Ownership with Continuous Harvest of Baits 20

5. Concluding Remarks 21

References.. 22

Appendix.. 25

Optimal Allocation of Anchovy Stocks as Baitfish for Tuna and Food for Local Communities in Developing Coastal Countries

Wisdom Akpalu*

Abstract

Bait tuna boats in developing coastal countries compete for small pelagic stocks such as anchovy that are primarily targeted by artisanal fishers. The tuna vessels are typically foreign owned, their catches are exported, and the vessels pay taxes to the resource-rich countries; by contrast, the artisanal fishers exploit the small pelagic stocks to support their livelihoods. In addition, the technologies employed in catching the baitfish (i.e., intermediate input) may destroy the benthic floor of the management area of artisanal stocks. Although these resource-use tradeoffs are common, bio-economic models that seek optimal allocation of such small pelagic species, as well as accounting for environmental opportunity costs, are rare. In this paper, such a model has been developed to verify the extent to which non-cooperative solutions deviate from social optimal outcomes when the tuna vessels are locally or foreign owned. Moreover, I have derived an expression for optimal (ad valorem) tax enough to maximize rents from the two stocks. The optimum solutions are characterized using data on tuna and anchovy fishing in Ghana.

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Keywords: fisheries; baitfish; developing country; bio-economic model

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*Author: Wisdom Akpalu (wakpalu@yahoo.com), Ghana Institute of Management and Public Administration (GIMPA), Accra, Ghana

1. Introduction

Coastal communities in developing countries largely depend on small pelagic species for the supply of fish and animal protein, employment and income (IPNLF, 2012; Vincent 2003; IOTC 2000; Blaber and Copland 1990). Small pelagic species, which are estimated to account for about 20-30% of global fish landings (Péron et al. 2010), are targeted by artisanal and subsistence fishers using boats, fishing nets and lines, traps, and outboard motors. With the rising population pressure and high unemployment in many coastal communities, coupled with lax formal management institutions, artisanal capture fisheries are generally overcapitalized and biologically overexploited (Gómez-Campos et al., 2011; Dalzell and Lewis, 1989). The stock depletion situation is further heightened by the extraction of common small pelagic stocks as baitfish by industrial fleets (Rawlinson et al. 1992; Gillett 2011a).

Catching baitfish has been found to be harmful to artisanal fisheries in many ways. These include harvest of juvenile fish that could become more valuable in the future; reducing the availability of food for piscivorous species that have market value; landing a significant amount of by-catch during bait fishing; and, most importantly, competing for the common stock with coastal communities that harvest the stock for their much needed animal protein (IPNLF, 2012; IOTC, 2000; Rawlinson, 1989; Ianelli and Ito, 1991). Although the competition for common stocks typically deepens the overfishing of small pelagic species, to the best of my knowledge, no bio-economic model has been developed to study the interaction of bait fishing by tuna fleets (that are often foreign owned) and landings of the same stock by artisanal fishers for food. Furthermore, tuna bait boats in many developing coastal countries employ fishing technologies that typically alter ecosystems and negatively impact the environmental carrying capacity of the targeted small pelagic stocks (IPNLF, 2012). In addition, in some cases, bait fishing is done within a relatively short period, which minimizes the potential damage to small pelagic stocks and marine ecosystems.

In this study, I have developed a bio-economic model that accounts for the competition for stocks (i.e., congestion externality) and the destruction of ecosystems, when tuna vessels are either local or foreign owned, and bait fishing is done continuously or instantaneously. To internalize the overfishing owing to competition and the damage to the ecosystem of small pelagic species, I propose and numerically simulate expressions for optimal taxation of bait fishing (i.e., a Pigouvian or corrective tax), drawing on data on Ghana. The results show that, compared to the case where tuna vessels are foreign owned, local owners of tuna vessels should pay a lower tax to mitigate the congestion externality. Moreover, if the tuna vessel is foreign owned, the ad valorem tax (tax on revenue from sale of catch) must be higher if baitfish catch occurs within a very short period (i.e., instantaneously), compared to the case where the baitfish is harvested continuously. Furthermore, regardless of the impact of the baitfish harvest on the ecosystem of the small pelagic stocks, the tax on baitfish catch should decrease in the social discount rate. If the vessels are foreign owned, the ad valorem tax should increase in the extent of damage to marine ecosystems and efficiency of the baitfish catching gear, but should decrease in the price of tuna and the cost of catching baitfish or tuna.

The remainder of the paper is organized as follows. The next section presents a brief discussion on the tuna and baitfish (anchovy) harvest in Ghana. This is followed by Section (3), which contains the theoretical models for the different scenarios mentioned earlier, the expressions for the optimal tax, and some comparative statistics analysis. Section (4) presents the simulated results and the last section (Section 5) contains the conclusions of the study.

2. The Tuna Fishing Industry in Ghana

Ghana has a coastline of 536km and a continental shelf measuring 23,700 km^2 with a depth of up to 200m (Williams 1968; Koranteng 1984). The nation's marine waters are part of the Gulf of Guinea, which is a large marine ecosystem (Sherman 1993). The Gulf of Guinea has species that live on or close to the bottom of the ocean (demersal species) and species that float at the middle or surface of the ocean (pelagic species). The small pelagic species fisheries largely depend on seasonal upwelling, which impacts spawning and increases biological productivity. The upwelling occurs twice a year: a minor one occurs from December to January, during the short cold season, and the major one from July to September, during the long cold season (Longhurst 1966; Mensah 1974). The major upwelling is characterized by a significant rise in the production of phytoplankton and zooplankton, as well as the spawning of most types of fish.

Tuna belongs to the class of large pelagic species; three species (bigeye, yellowfin, and skipjack tuna) are found in Ghana's waters. Historically, the Gulf of Guinea is rich in tuna species. Commercial tuna fishing in Ghana began in 1962 and relied on two species (anchovy and young sardines) as live baitfish (Kwadjosse, 2009). The two small pelagic species were in abundance in the Ghanaian waters until the collapse of the sardinella fisheries in the 1970s. Although the relative catch of the two species as baitfish depends on their abundance, studies have found that anchovy is preferred to sardine because it is available most of the year and survives longer when kept under artificial conditions (Choo and Kim, 1998). In addition, skipjack, which accounts for a disproportionate amount of the tuna catch (72% in 2016), are attracted to anchovy (Baldwin, 1977). Beginning in 1977, after the collapse of sardine fisheries due to overfishing, anchovy, which accounts for over a quarter of the total marine landings in Ghana, became the only species used as live baitfish (Koranteng, 1993; Nunoo et al., 2014). Figures 1 and 2 show the proportion of anchovy catch used as baitfish and tuna landings in Ghana, respectively.

From Fig. 1, the proportion of baitfish in total landings of anchovy was 3.6% in 1987 but rose steadily to about 14% in 1993. The highest figure of 24% was recorded in 2007 – implying a sharp decline in the anchovy catch for food – after which it declined to an average of 5%. Although the heaves are hard to explain, total baitfish landings were between 4000-5000 metric tons between 1990 and 2003, and only declined to between 2000 and 3000 metric tons from 2004 to 2014. This is non-trivial, since about 58% of fish for domestic consumption is currently imported to meet the per capita annual consumption of 23kg. Further, from Fig. 2, the tuna catch, which stood at about 35,000 metric tons, increased by 141% in 1999 and averaged 72,000 metric tons between 1999 and 2016.

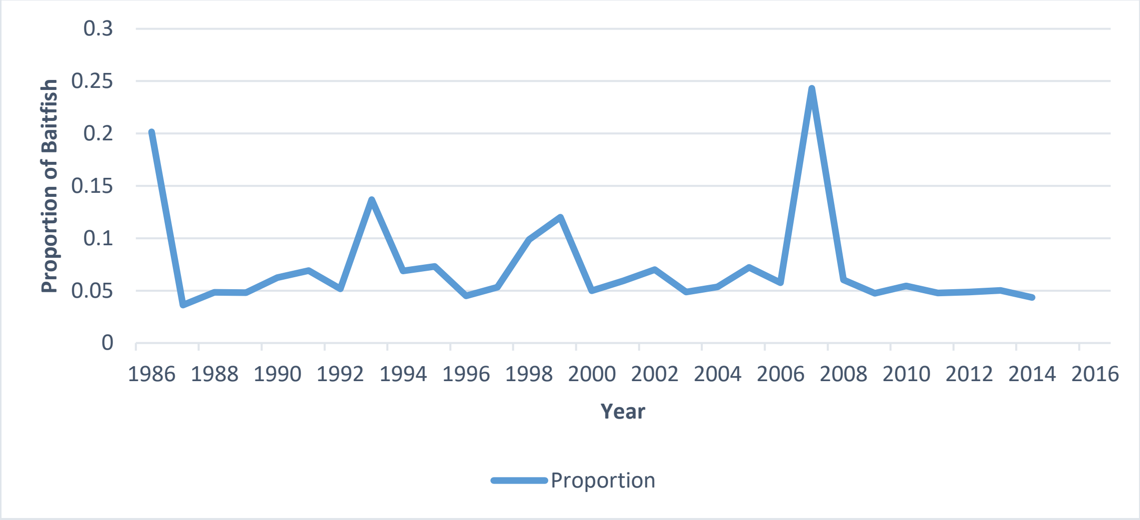

Figure 1. Proportion of Tuna Baitfish (Anchovy) in Total Landings in Ghana (1986-2014)

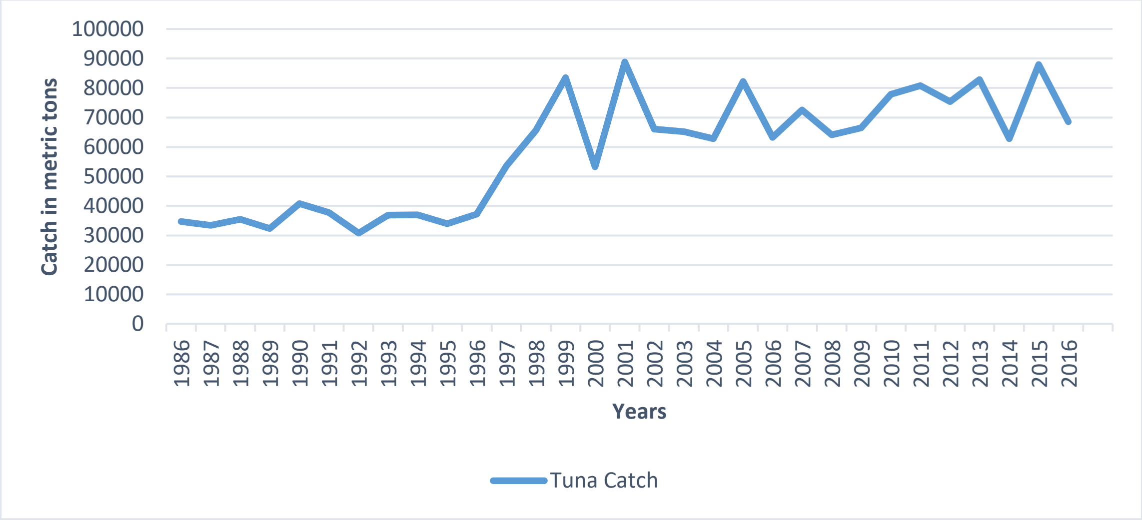

Figure 2. Tuna Landings in Ghana (1986-2016)

With anchovy stocks declining owing to adverse climatic conditions and overfishing, beginning in the 1980s, the tuna bait-boats spent a considerable amount of time catching baitfish, typically within the inshore exclusive zone (IEZ) of less than 30m that is reserved for artisanal fishers (Mensah, 1983). As noted by Baldwin (1977), anchovy form large schools nearshore throughout the year. The extraction technique involves using a special pursing net to circle the anchovy. In some cases, underwater lights are used to aggregate the baitfish before circling them (Dalzell and Lewis 1989; Hallier et al. 1982). Currently there are 20 tuna bait boats, making six 45-day trips annually on average. The baitfish are then stored in wells or tanks on tuna vessels (Kwei et al., 1995).

Stock assessment reports have found that the current tuna harvest levels are sustainable. However, with the increased competition for anchovy as baitfish and fish protein for the growing local population, there is evidence of biological overfishing of the anchovy stock within the IEZ. This has serious implications for livelihoods within and outside of the artisanal fishing communities. For example, between 1986 and 2016, anchovy catch constituted about 35% of artisanal landings, and small-scale fishing currently employs about 20% of the active labor force.

3. The Theoretical Model

As noted earlier, anchovy in Ghanaian waters are targeted by artisanal fishers for fish protein and by tuna fishers as baitfish (i.e., intermediate input). To quantify the extent to which non-cooperative solutions deviate from socially optimal outcomes, and to determine the tax necessary to ensure a sustainable catch, the social planner's problem is presented first, followed by the optimization programs of the anchovy and tuna fishers, which generate sub-optimal equilibrium outcomes.

3.1 The Cooperative Outcome: The Social Planner's Program

Suppose a social planner's objective is to maximize the aggregate surplus from both (tuna and anchovy) fisheries. Let A represent the stock (biomass) of anchovy targeted by the tuna fleets and artisanal fishers within a management area (e.g., the nation's exclusive economic zone (EEZ)). Define the catch (in biomass) by a typical tuna fleet and an artisanal fisher, who target anchovy, as A_1 and A_2, respectively. Some studies have assumed a constant catchability coefficient, but others have argued for a more complex structure which is influenced by baits (see, e.g., Skud, 1978; Richards and Schnute, 1986; Løkkeborg and Bjordal 1992; Bjordal and Løkkeborg, 1996; Tutui and Braga 2007). Following the latter, I model the catchability coefficient of the tuna fleet as a linear function of the biomass of anchovy caught (i.e.,$q(A_1) = \sigma A_1$), where σ is a constant.

Suppose tuna catch, which is mainly for export, is traded in a perfectly competitive international market at the price per kilogram of p, and the tuna catch and fishing cost follow Schaefer functions. Without loss of generality, suppose the same technology is employed for catching anchovy as baitfish and as fish protein, so that the cost function is $\gamma(A)A_i$. Thus, $\gamma(A)A_1$ and $\gamma(A)A_2$ are the cost of fishing anchovy as baitfish and fish protein, respectively. Note that the cost per unit harvest (i.e., $\gamma(A)$) is assumed to be the same for both fleets. Let the instantaneous revenue from the sale of tuna catch be $pq(A_1)Ex$, where E and x are tuna fishing effort and stock, respectively. The cost of fishing tuna is the sum of the direct cost of catching tuna cE (where c is constant cost per unit effort of fishing tuna) and the cost of catching the baitfish (i.e., anchovy) (i.e., $\gamma(A)A_1$). Furthermore, let future costs and benefits be discounted at a positive social discount rate $\delta(> 0)$. The social planner's optimization program entails maximizing the value function given by equation (1) subject to the tuna and anchovy stock dynamic equations (equations 2 and 3). That is,

$$\underset{\{E,A_1,A_2\}}{Max} \int_0^{\infty}\left(pq(A_1)Ex + bA_2 - cE - \gamma(A)(A_1 + A_2)\right)e^{-\delta t}\,dt \tag{1}$$

Subject to:

$$\dot{x} = g(x) - q(A_1)Ex \tag{2}$$

$$\dot{A} = f(A) - A_1 - A_2 \tag{3}$$

with $q(0) = 0, q_{A_1} > 0$, $q_{A_1A_1} \leq 0$, $\gamma_A < 0$, $\gamma_{AA} \geq 0, g_x > 0$, $g_{xx} \leq 0, f_A > 0$, $f_{AA} \leq 0$.

Note that $g(x)$ and $f(A)$ are the growth functions of the tuna and anchovy stocks, respectively. Equation (2) stipulates that the time derivative of the tuna stock is increasing in growth but decreasing in the catch of tuna, which is a function of the availability of baitfish (i.e., anchovy). Also, equation (3) indicates that the difference in the anchovy stock between two periods depends on its growth and on the catch by the tuna fleets and the local fishers who fish for food. The value function sums up the net benefit from fishing tuna (i.e., $pq(A_1)Ex - cE - \gamma(A)A_1$) and anchovy (i.e., $bA_2 - \gamma(A)A_2$). The corresponding current value Hamiltonian (CVH) for the optimization program is equation (4).

$$\begin{aligned} H(A_1, A_2, E, x, \lambda, \psi) = pq(A_1)Ex + bA_2 - cE - \gamma(A)(A_1 + A_2) + \lambda_s(g(x) - q(A_1)Ex) \\ + \mu_s(f(A) - A_1 - A_2), \end{aligned} \tag{4}$$

where λ_s and μ_s are the shadow values of the tuna and anchovy stocks, respectively. The maximum principle, based on equation (4), generates the first order conditions (5-7) for the three flow variables E, A_1 and A_2, respectively, assuming interior solutions exist.

$$p - \frac{c}{q(A_1)x} = \lambda_s \tag{5}$$

$$(p - \lambda_s)q_{A_1}(A_1)Ex - \gamma(A) = \mu_s \tag{6}$$

$$b - \gamma(A) = \mu_s \tag{7}$$

The corresponding co-state equations for the two stocks, x and A, are equations 8 and 9, respectively:

$$\dot{\lambda}_s - \delta\lambda_s = -pq(A_1)E - \lambda_s(g_x(x) - q(A_1)E) \tag{8}$$

$$\dot{\mu}_s - \delta\mu_s = \gamma_A(A)(A_1 + A_2) - \mu_s f_A(A) \tag{9}$$

From equation (5), in inter-temporal equilibrium, the net marginal surplus from fishing tuna (i.e., $p - \frac{c}{q(A_1)x}$) must equate the scarcity value of the tuna stock (i.e., λ_s). Furthermore, equation (6) indicates that the *marginal yield* of the baitfish (anchovy), valued at the price of tuna net its scarcity value (i.e., $(p - \lambda_s)q_{A_1}(A_1)Ex$), should reflect the opportunity cost of catching the baitfish (i.e., marginal private cost plus the shadow price of the baitfish) when in equilibrium (i.e., $\mu_s + \gamma(A)$). Next, for the anchovy harvested for direct consumption, at equilibrium, the net marginal benefit (i.e., $b - \gamma(A)$) should reflect its scarcity value (i.e., μ_s). In steady state, $\dot{\mu}_s = \dot{\lambda}_s = 0$, the co-state equations, yield

$$\lambda_s = \frac{pq(A_1)E}{\delta + q(A_1)E - g_x(x)} \tag{10}$$

$$\mu_s = \frac{\gamma_A(A)(A_1 + A_2)}{f_A(A) - \delta} \tag{11}$$

Using equation (10) in (5) gives

$$p - \frac{c}{q(A_1)x} = \frac{pg(x)}{\delta x + g(x) - g_x(x)x} \tag{12}$$

Furthermore, substituting equations (10) and (11) into (6) and noting that $g(x) = q(A_1)Ex$ generates equation (13).

$$\left(\frac{pg(x)(\delta-g_x(x))x}{(\delta-g_x(x))x+g(x)}\right)\left(\frac{q_{A1}(A_1)}{q(A_1)}\right)=b \tag{13}$$

Using equation (27) in (31) also gives

$$b-\gamma(A)=\left(\frac{\gamma_A(A)(A_1+A_2)}{f_A(A)-\delta}\right)=\frac{\gamma_A(A)f(A)}{f_A(A)-\delta} \tag{14}$$

Equations (12) through (14) generate the optimal (cooperative) catch and stock levels of both species. In the absence of catching anchovy as baitfish (i.e., $A_1 = 0$), both the optimal catch by the artisanal fishers and the stock of the anchovy must be higher. In equilibrium, the gain from fishing tuna must therefore offset the loss in artisanal catch revenues due to the congestion externality.

3.2 Non-Cooperative Outcomes

Now suppose each of the two fishers (the operator of the tuna fleet and the artisanal fisher) is self-interested and maximizes his/her surplus/value function, subject to the stock dynamic equation(s). Due to congestion externalities, the equilibrium extraction levels of the agents are likely to deviate from the socially optimal levels of the social planner. To quantify the extent of the deviations, the optimization program of the anchovy fisher is presented, followed by that of the tuna fisher, and a tax expression necessary to internalize the externality (i.e., account for the deviation) is derived.

3.3 The Anchovy Fleet

Following the social planner's program, the anchovy fisher's objective is to maximize the stream of net benefits from anchovy landings subject to the fish stock dynamic equation. The objective function and the constraint are given by equations (15) and (16), respectively. That is, maximize equation (15):

$$\underset{\{A_2\}}{Max}\int_0^{\infty}(bA_2-\gamma(A)A_2)\,e^{-\delta t}dt, \tag{15}$$

subject to:

$$\dot{A}=f(A)-A_1-A_2 \tag{16}$$

The CVH corresponding to the above is $H(A_2,\mu)=bA_2-\gamma(A)A_2+\mu(f(A)-A_1-A_2)$, where μ is the shadow value of the anchovy stock. The maximum principle generates equation (18), which is the first order condition, and the co-state equation is given by equation (19).

$$b - \gamma(A) = \mu \tag{18}$$

$$\dot{\mu} - \delta\mu = \gamma_A(A)A_2 - \mu f_A(A) \tag{19}$$

From equation (18), the equilibrium catch of anchovy for food will be at the level where the inter-temporal marginal net benefit from the catch (i.e., $b - \gamma(A)$) equates the scarcity value of the anchovy stock (μ). In a dynamic equilibrium, the capital gain from the differing catch for a period plus the stock effect (i.e.,$\dot{\mu} + (\mu f_A(A) - \gamma_A(A)A_2)$) must balance returns on investing the scarcity value of the anchovy, if catch is not delayed (i.e.,$\delta\mu$). The steady state ($\dot{\mu} = \dot{A} = 0$) solution generates the following implicit reaction function:

$$b - \gamma(A) - \frac{\gamma_A(A)(f(A) - A_1)}{f_A(A) - \delta} = 0 \tag{20}$$

From equation (20), the optimal anchovy catch by artisanal fishers depends on the landings of the tuna fleet.

3.4 The Tuna Fleet

Since the tuna fisher targets both tuna and anchovy stocks, he/she will maximize a surplus function given by equation (21), subject to the two stock dynamic equations (equations 22 and 23). The optimization program is as follows:

Maximize

$$\underset{\{E,A_1\}}{Max} \int_0^\infty (pq(A_1)Ex - cE - \gamma(A)A_1)\, e^{-\delta t} dt, \tag{21}$$

subject to

$$\dot{x} = g(x) - q(A_1)Ex, \tag{22}$$

and

$$\dot{A} = f(A) - A_1 - A_2. \tag{23}$$

Let λ and ψ represent the shadow values of the tuna and anchovy stocks, respectively. The corresponding CVH generates the following first order conditions for the two flow variables E and A_2, respectively.

$$p - \frac{c}{q(A_1)x} = \lambda \tag{24}$$

$$(p-\lambda)q_{A_1}(A_1)Ex-\gamma(A)=\psi \tag{25}$$

Equation (24) is similar to (5), and hence stipulates that, in inter-temporal equilibrium, the tuna fisher will equate the net marginal benefit from catching tuna (which depends on the availability of the baitfish) to the scarcity value of tuna (λ). Similarly, equation (25) could be interpreted as (6). The corresponding co-state equations for the tuna and anchovy stocks are:

$$\dot{\lambda}-\delta\lambda=-pq(A_1)E-\lambda(g_x(x)-q(A_1)E) \tag{26}$$

$$\dot{\psi}-\delta\psi=\gamma_A(A)A_1-\psi f_A(A) \tag{27}$$

Equation (26) is same as (8), but equations (27) and (9) are different. A portion of the stock effect on the cost of harvest in equation (9) (i.e., $\gamma_A(A)A_2$) is neglected by the tuna fisher, hence does not appear in equation (27). The steady state equilibrium solutions are:

$$p-\frac{c}{q(A_1)x}=\frac{pg(x)}{\delta x+g(x)-g_x(x)x} \tag{28}$$

$$\left(\frac{pg(x)\left(\delta-g_x(x)\right)x}{\left(\delta-g_x(x)\right)x+g(x)}\right)\left(\frac{q_{A1}(A_1)}{q(A_1)}\right)=\frac{\gamma_A(A)A_1}{f_A(A)-\delta}+\gamma(A) \tag{29}$$

where $A_1=f(A)-A_2$, from the stock dynamic equation.

3.5 The Economic Policy Instrument

As earlier noted, the anchovy catch exceeds the quantity required to derive the optimal rent from the resource. To internalize the congestion externality, the tuna fleet must be taxed. There is evidence in the literature of bait fishers being forced to pay access fees (IPNLF, 2012; Rawlinson et al., 1992; Sharma and Adams, 1990). Following Akpalu and Parks (2007), the expression for tax on baitfish catch is obtained by comparing equations (9) and (27) in steady state (i.e., $\tau=\mu_s-\psi$). Thus, the tax expression is:

$$\tau^*=\frac{-\gamma_A(A^*)(f(A^*)-A_1^*)}{\delta-f_A(A^*)} \tag{30}$$

Note that the stars represent the equilibrium values of the corresponding variables. It can be shown that the optimum tax rate must decrease when the anchovy stock increases, all else equal. Thus,

$$\frac{\partial \tau^*}{\partial A^*} = \tau^* \left(\frac{\gamma_{AA}(A^*)}{\gamma_A(A^*)} + \frac{f_{AA}(A^*)}{\delta - f_A(A^*)} - \frac{f_A(A^*)}{f(A^*) - A_1^*} \right) < 0$$

3.6 The Use of Destructive Baitfish Fishing Methods

Furthermore, tuna bait-boats compete with artisanal fishing boats inshore for anchovy. Whilst the artisanal fishers employ simple and ecologically less-harmful technologies, the bait-boats may use technologies that could plane-off the benthic floor of the ocean and therefore impact the environmental carrying capacity of the anchovy stock. To account for this externality, following Akpalu and Worku (2011), I surmise that the growth function of anchovy is $f(A, A_1) = rA\left(1 - \frac{A}{k - vA_1}\right)$, so that the corresponding equation of motion is:

$$\dot{A} = f(A, A_1) - A_1 - A_2 \tag{31}$$

Using the anchovy growth function in the preceding optimization program, and assuming interior solutions exist, I obtain the following steady state equations, which can be solved for the optimal stock and flow variables, as well as the tax rate.

$$\left(\frac{px(\delta - g_x(x))g(x)}{\delta x + g(x) - g_x(x)x}\right)\left(\frac{q_{A_1}(A_1)}{q(A_1)}\right) = \gamma(A) - \left(\frac{\gamma_A(A)f(A,A_1)}{\delta - f_A(A,A_1)}\right)\left(1 - f_{A_1}(A, A_1)\right) \tag{32}$$

$$p - \frac{c}{q(A_1)x} = \frac{pg(x)}{\delta x + g(x) - g_x(x)x} \tag{33}$$

$$b - \gamma(A) = -\frac{\gamma_A(A)f(A,A_1)}{\delta - f_A(A,A_1)} \tag{34}$$

Comparing equations (32) through (34) with the cooperative solutions, the corresponding expression for the tax is:

$$\tau^{**} = \frac{pg(x^*) - c\left(\frac{g(x^*)}{q(A_1^{**})x^*}\right) - \gamma(A^{**})A_1^{**}}{pg(x^*)} \tag{35}$$

It can be shown that, due to the negative externality, the catch of baitfish and tuna must decrease, whilst the landings of anchovy for fish protein must increase. Moreover, the ad valorem tax must increase to account for the environmental opportunity cost (i.e., $\tau^{**} > \tau^{*}$).

3.7 The Foreign Tuna Fleet: Social Planner's Problem

The tuna vessels fishing in distant waters in Ghana are predominantly foreign owned. Now suppose the foreign fleet pays ad valorem tax denoted $\tau^{/}$ to the resource-rich country (e.g., Ghana). The social planner's optimization program entails maximizing the sum of the tax revenue from tuna catch and net revenue from anchovy catch (i.e., equation 36), subject to the two stock evolution equations and an isoperimetric constraint (i.e., equation 39). Thus,

$$\underset{\{E,A_1,A_2\}}{Max} \int_0^{\infty} (\tau pq(A_1)Ex + bA_2 - \gamma(A)A_2)e^{-\delta t}dt \tag{36}$$

Subject to:

$$\dot{x} = g(x) - q(A_1)Ex \tag{37}$$

$$\dot{A} = f(A) - A_1 - A_2 \tag{38}$$

$$\int_0^{\infty} \left((1-\tau^{/})pq(A_1)Ex - cE - \gamma(A)A_1\right) e^{-\delta t}dt \geq 0 \tag{39}$$

As in Akpalu and Parks (2007), the isoperimetric constraint stipulates that the stream of rents accruing to the tuna fisher must be non-negative. The corresponding current value Hamiltonian of the problem and the associated Lagrangian function are equations (40) and (41), respectively;

$$H(\bullet) = \tau pq(A_1)Ex + bA_2 - \gamma(A)A_2 + \lambda(g(x) - q(A_1)Ex) + \psi(f(A) - A_1 - A_2) \tag{40}$$

$$L(A_1, A_2, \alpha, E, x, \lambda, \psi) = H(\bullet) + \phi\left((1-\tau^{/})pq(A_1)Ex - cE - \gamma(A)A_1\right) \tag{41}$$

The first order conditions of the Lagrangian function, with regard to the flow variables, assuming interior solutions exist, are equations (47) through (51).

$$\frac{dL}{d\alpha} = 0 \rightarrow \phi = 1 \tag{42}$$

$$\frac{dL}{dE} = 0 \rightarrow p - \frac{c}{q(A_1)x} = \lambda \tag{43}$$

$$\frac{dL}{dA_1} = 0 \rightarrow (p - \lambda)q_{A_1}(A_1)Ex - \gamma(A) = \psi \tag{44}$$

$$\frac{dL}{dA_2} = 0 \rightarrow b - \gamma(A) = \psi \tag{45}$$

$$\frac{dL}{d\phi} = 0 \rightarrow \left(1 - \tau^{/}\right)pq(A_1)Ex = cE + \gamma(A)A_1 \tag{46}$$

Equations (43) through (45) are the same as those obtained earlier from the social planner's problem and have the same interpretations. The additional equations (42) and (46) are worth discussing. The former indicates that the value of the Lagrangian multiplier is constant and the latter implies that, in inter-temporal equilibrium, pure profit from fishing tuna is zero. The co-state equations associated with the two stock variables x and A are as follows:

$$\dot{\lambda} - \delta\lambda = -\frac{dH}{dx} = -pq(A_1)E - \lambda(g_x(x) - q(A_1)E) \tag{47}$$

$$\dot{\psi} - \delta\psi = -\frac{\partial H}{\partial A} = \gamma_A(A)(A_1 + A_2) - \psi f_A(A) \tag{48}$$

Again, equations (47) and (48) are the same as (8) and (9), respectively. In steady state, $\dot{\lambda} = \dot{\psi} = 0$, hence

$$\lambda = \frac{pq(A_1)E}{\delta + q(A_1)E - g_x(x)}, \tag{49}$$

and

$$\psi = -\frac{\gamma_A(A)f(A)}{\delta - f_A(A)} \tag{50}$$

Using equations (43) and (45) in (49) and (50), respectively, gives the following:

$$p - \frac{c}{q(A_1)x} = \frac{pg(x)}{\delta x + g(x) - g_x(x)x} \tag{51}$$

$$b - \gamma(A) = -\frac{\gamma_A(A)f(A)}{\delta - f_A(A)} \tag{52}$$

$$\left(\frac{px\left(\delta-g_x(x)\right)}{\delta x+g(x)-g_x(x)x}\right)\left(\frac{q_{A_1}(A_1)}{q(A_1)}\right)g(x)=b \tag{53}$$

Moreover, from equation (46), the expression for the optimal ad valorem tax is derived as follows:

$$\tau^{/*}=\frac{pg\left(x^{/*}\right)-c\left(\frac{g\left(x^{/*}\right)}{q\left(A_1^{/*}\right)x^{/*}}\right)-\gamma\left(A^{/*}\right)A_1^{/*}}{pg\left(x^{/*}\right)} \tag{54}$$

The tax expression is the ratio of the resource rents (net revenue) to the total revenue obtainable from biomass growth of the tuna stock. Specifically, to harvest the ‘growth in the biomass of tuna’, two costs are incurred: the direct cost of fishing tuna, and the indirect cost, which is the cost of fishing anchovy.

3.8 Instantaneous Harvest Function of Tuna Fishers

The earlier specification of the model is premised on continuous harvesting of the baitfish. Consider a more realistic situation where the baitfish is extracted within a short period. Following Akpalu et al. (2008) and Tahvonen (2008), which are based on the escapement models of Reed (1979) and Clark (1990), I define the instantaneous harvest growth function as $f(A,A_1)=rz\left(1-\frac{z}{k}\right)$, where $z=A-A_1$, and the cost function as $\eta(A,A_1)=\int_{A-A_1}^{A}\left(\frac{\eta}{z}\right)dz=\eta\, ln\left(\frac{A}{A-A_1}\right)$. The corresponding optimization program consists of equations (55) through (58). That is,

$$\underset{\{E,A_1,A_2\}}{Max}\int_0^{\infty}(\tau pq(A_1)Ex+bA_2-\gamma(A)A_2)e^{-\delta t}dt \tag{55}$$

Subject to:

$$\dot{x}=g(x)-q(A_1)Ex \tag{56}$$

$$\dot{A}=f(A,A_1)-A_2-A_1 \tag{57}$$

$$\int_0^{\infty}\left((1-\tau)pq(A_1)Ex-cE-\eta(A,A_1)\right)e^{-\delta t}dt\geq 0 \tag{58}$$

Following the optimization routine, the steady state solutions are:

$$p-\frac{c}{q(A_1)x}=\frac{pg(x)}{\delta x+g(x)-g_x(x)x} \tag{59}$$

$$b-\gamma(A)=-\frac{\left(\gamma_A(A)(f(A,A_1)-A_1)+\eta_A(A,A_1)\right)}{\left(\delta-f_A(A,A_1)\right)} \tag{60}$$

$$\left(\frac{px\left(\delta-g_x(x)\right)}{\delta x+g(x)-g_x(x)x}\right)\left(\frac{q_{A_1}(A_1)}{q(A_1)}\right)g(x)=\eta_{A_1}(A,A_1)+\left(b-\gamma(A)\right)\left(1-f_{A_1}(A,A_1)\right) \tag{61}$$

$$\tau^{/**}=\frac{pg\left(x^{/**}\right)-c\left(\frac{g\left(x^{/**}\right)}{q\left(A_1^{/**}\right)x^{/**}}\right)-\eta\left(A^{/**},A_1^{/**}\right)}{pg\left(x^{/**}\right)} \tag{62}$$

Note that $f(A)>f(A,A_1)$, $f_{A_1}(A,A_1)<0$ and $\eta(A,A_1)>\gamma(A)A_1$, $\forall A_1>0$. The equilibrium extractions and stock levels can be computed from equations (59) through (61) and $f(A,A_1)=A_2+A_1$, which comes from equation (57). If equations (59) through (62) are compared with (28) through (30), the tax rate for the instantaneous extraction of the baitfish should be lower (i.e., $\tau^{/**}<\tau^{*}$).

4. Numerical Illustration of the Results

4.1 The Sustainable Yield Functions

To numerically solve for the optimal values of the stocks and catches, a specific functional form for the catchability coefficient of the tuna baiting fleet is assumed and verified empirically. Let the catchability coefficient be time variant and assume it is linearly dependent on the baitfish (anchovy) (see Wilberg et al. 2009, for an extensive review of literature on time-varying catchability coefficients). As noted by Kwei et al. (1995), any decrease in the anchovy stock will impact the bait-boat performance. Hence $q_t=q(A_{1t})=\sigma^T A_{1t}$, where σ^T is a constant. The corresponding sustainable yield (per baitfish landing) function that is empirically estimated is:

$$\left(\frac{Y}{A_1}\right)_t=\hat{\alpha}E_t-\hat{\beta}(A_{1t}E_t^2)+e_t \tag{63}$$

where the parameters to be estimated are $\hat{\alpha}(=\sigma^T k)$ and $\hat{\beta}\left(=\frac{\sigma^{T2}k}{r}\right)$, and e_t is a normally distributed error term. Furthermore, let the sustainable yield function of the anchovy fisher be equation (64), where $\hat{a}(=\sigma^A k^A)$ and $\hat{b}\left(=\frac{\sigma^{A2}k^A}{r^A}\right)$ are parameters to be estimated, and φ_t is a normally distributed error term.

$$Y_{A_2}=\hat{a}E_{A_2t}-\hat{b}E_{A_2t}^2+\varphi_t \tag{64}$$

4.2 The Data and Numerical Illustrations

Time series data spanning 1986 through 2016, collected from the Fisheries Scientific Survey Division (FSSD) of the Fisheries Commission (FC) in Ghana, was used to estimate equations (63) and (64). The variables of interest include tuna catch per baiting fleet, number of vessels, and anchovy catch by bait boats and artisanal fishers. The descriptive statistics of the data are presented in Table 1. The annual mean landings of anchovy as baitfish equals about 6% of tuna landings, and each of the tuna vessels landed over 2000 metric tons a year, on average, compared to the yearly mean anchovy landings of about 14 metric tons by the artisanal boats.

Table 1. Descriptive Statistics of Tuna and Anchovy Catches and Fishing Vessels/Boats in Ghana (1986-2016)

Variables	**Mean**	**Standard Deviation**
Anchovy Catch by Artisanal Fishers (metric tons)	56046.22	22689.37
Anchovy Catch by Bait Boats (metric tons)	3534.345	896.13
Tuna Catch (metric tons)	58509.29	19403.4
# of Tuna Vessels	29	7.3098
# of Canoes	3796	1367.56

4.3 The Sustainable Yield Regression Results

The F-statistics from the regression results, reported in Tables 3 and 4, indicate that the data fits the models at the 1% significance level. Furthermore, the R-squared from both tables show that about 88% and 90% of the variability in the dependent variables in Tables 3 and 4, respectively, are explained. Moreover, all the estimated coefficients are statistically significant at the 1% level. Using the intrinsic growth rate of 1.52 for tuna and 1.8 for anchovy, the catchability coefficient of the anchovy fleet, the baitfish catch efficiency coefficient, and the environmental carrying capacity are calculated.

Table 2. Description of Parameters for the Empirical Analysis

Parameters	**Description**
$\boldsymbol{c}$	Cost per unit harvest of tuna
$\boldsymbol{p}$	Price per kilogram of tuna
δ	Discounting rate
$\boldsymbol{\alpha}; \boldsymbol{\beta}$	Regression coefficients for the tuna fisher
$\boldsymbol{\theta}; \boldsymbol{\varsigma}$	Regression coefficients for the anchovy fisher
$\boldsymbol{\sigma_a}$	Catchability coefficient for the anchovy fisher
$\boldsymbol{\sigma_t}$	Catchability coefficient for the tuna fisher
k_a	Environmental carrying capacity for anchovy
k_t	Environmental carrying capacity for tuna
$\boldsymbol{r_a}$	Intrinsic growth rate for anchovy
$\boldsymbol{r_t}$	Intrinsic growth rate for tuna
$\boldsymbol{b}$	Price per kilogram of anchovy
$\boldsymbol{\gamma}$	Cost per unit harvest of anchovy

Table 3. Ordinary Least Square (OLS) Regression of Sustainable Tuna Yield Function in Ghana

Variable	**Coefficient**
Effort (# of Vessels)	1.588558(0.153)***
Tuna Bait (i.e., anchovy)*Effort-Squared	-0.000008 (0. 11x10^{-5})***
Prob > Chi-squared	0.0000
F-statistic	7.87***
Number of observations	29
R-squared	0.88

*** implies significant at 1% level.

Table 4. Ordinary Least Square (OLS) Regression of Sustainable Anchovy Yield Function in Ghana

Variable	**Coefficient**
Effort (# of Canoes)	28.591 (3.179)***
Effort-Squared	-0.0032 (0.0006)***
Prob > Chi-squared	0.0000
F-statistic	177.72***
Number of observations	31
R-squared	0.90

*** implies significant at 1% level.

4.4 Numerical Simulations

4.4.1 Local Tuna Fleet Ownership and Cooperative Solution

Besides the biophysical parameters, the values of all other parameters in our models are assumed and varied for computational convenience. These include the prices of tuna and anchovy, the cost per unit effort of the artisanal and tuna fleets, and the social discount rate. As a result, our emphasis is on the direction of change of the flow and stock variables but not on the specific numerical values. Table 5 presents the results of the numerical simulations of the social planner's problem (equations 12 through 14). As noted earlier, this illustrates the situation where tuna vessels are locally owned and bait fishing does not negatively impact the marine ecosystem. The total (optimal) landing is 59,190.6 metric tons, which is very close (99.34%) to the mean landing reported in Table 1. Furthermore, the estimated (optimal) tuna landing is 13% higher than the reported mean catch but significantly lower than the highest recorded landing, and the equilibrium proportion of the baitfish to tuna landing is estimated at approximately 11.7%.

The results indicate that choosing a higher social discount rate (δ), all else equal, will increase the equilibrium tuna and anchovy landings, and thereby lower the stocks of both fisheries. Thus, placing higher values on immediate reward from the fisheries can lead to excessive exploitation and, consequently, fish stock depletion. On the other hand, elevated levels of efficiency of the fishing gear used to land anchovy (σ_t), all else equal, will increase tuna landing and decrease the equilibrium landing of the baitfish, but increase equilibrium anchovy catch by artisanal fishers.

Table 5. The Effect of Social Discount Rate and Increased Efficiency in Bait Fishing on Tuna and Anchovy Catches and Stocks

Parameters & Variables	Baseline	$\boldsymbol{\Delta\delta}\uparrow$	$\boldsymbol{\Delta\sigma_t}\uparrow$
c	100	100	100
p	0.02	0.02	0.02
δ	0.03	**0.05**	0.03
$\alpha; \beta$	1.588558;0.000008	1.588558;0.000008	1.588558;0.000008
$\theta; \varsigma$	28.591; 0.0032	28.591; 0.0032	28.591; 0.0032
σ_a	0.000201462	0.000201462	0.000201462
σ_t	0.00000765	0.00000765	**0.0000765**
k_a	141917.5835	141917.5835	141917.5835
k_t	207526.0296	207526.0296	207526.0296
r_a	1.8	1.8	1.8
r_t	1.52	1.52	1.52
b	0.1	0.1	0.1
γ	0.8	0.8	0.8
Anchovy stock (A)	90151.9	89715.0	90151.9
Tuna stock $\left(x^*\right)$	145220.0	144359.1	112970.1
Tuna baitfish(A_1)	7723.6	7776.8	3008.8
Anchovy catch(A_2)	51467.0	51624.2	56181.8
Tuna catch $\left(h^*\right)$	66271.6	66789.0	78239.0

4.5 Local Tuna Fleet Ownership and Non-Cooperative Solution

The third column of Table 6 contains the results of the non-cooperative outcomes and the tax on baitfish catch that would be enough to internalize the congestion externality. From the results, the total anchovy landing and baitfish catch are higher in the non-cooperative case, and the equilibrium stock is lower, than the optimal levels. Thus, in the absence of a baitfish quota, the social planner can impose an ad valorem tax (of 5.48%) on the price of tuna to account for the environmental opportunity cost. From the comparative statics analysis (Table 7, and 7A at Appendix A), the tax rate is decreasing in the social discount rate, the price of tuna, and the cost of catching anchovy and tuna, but increasing in anchovy fishing gear efficiency. Thus, a higher social discount rate, which is consistent with society placing a lower value on future benefits from the fishery, promotes intensification of fishing efforts. In that case, tuna fishers should pay a lower tax rate for catching anchovy as baitfish. Furthermore, if the cost of fishing anchovy or tuna increases, all else equal, tuna fishing would become less profitable; in that case, the tax rate should decrease.

In addition, if the price of tuna increases, a smaller proportion of the price would be enough to account for the environmental externalities, implying the tax rate should be decreasing in the price of tuna. On the other hand, if the technology for catching anchovy improves or the fishing gear becomes more efficient, the tax rate must rise to moderate the depletion of the anchovy stock and maximize inter-temporal rents.

Table 6. Parameters used for Numerical Simulations and Corresponding Optimal Values

Parameters & Variables	Social Planner: First Best Solution	Local Tuna Fleet: Non-Cooperative Outcome	Foreign Tuna Fleets: Continuous Harvest of Bait	Foreign Fleet: Instantaneous Harvest of Bait	Local Tuna Fleet: Bait Fishing Damage Ocean Floor
c	100	100	100	100	100
p	0.02	0.02	0.02	0.02	0.02
δ	0.03	0.03	0.03	0.03	0.03
$\alpha; \beta$	1.588558; 0.000008	1.588558; 0.000008	1.588558; 0.000008	1.588558; 0.000008	1.588558; 0.000008
$\theta; \varsigma$	28.591; 0.0032	28.591; 0.0032	28.591; 0.0032	28.591; 0.0032	28.591; 0.0032
σ_a	0.000201462	0.000201462	0.000201462	0.000201462	0.000201462
σ_t	0.00000765	0.00000765	0.00000765	0.00000765	0.00000765
k_a	141917.5835	141917.5835	141917.5835	141917.5835	141917.5835
k_t	207526.0296	207526.0296	207526.0296	207526.0296	207526.0296
r_a	1.8	1.8	1.8	1.8	1.8
r_t	1.52	1.52	1.52	1.52	1.52
b	0.1	0.1	0.1	0.1	0.1
γ	0.8	0.8	0.8	0.8	0.8
υ	0.000	0.000	0.000	0.000	0.5
Anchovy stock (A)	90151.933	87854.795	90151.933	91677.403	96480.075
Tuna stock $\left(x^*\right)$	145219.97	131292.81	145219.97	204023.26	137537.74
Tuna baitfish(A_1)	7723.602	11393.44	7723.602	3258.370	9394.313
Anchovy catch(A_2)	51467.0	48848.7	51467.0	56737.9	46207.4
Tuna catch $\left(h^*\right)$	66271.6	73308.8	66271.6	5234.34	70504.7
Total anchovy catch $(A_1 + A_2)$	59190.6	60242.1	59190.6	59996.2	55601.7
Tax $\left(\tau'\right)$	---	5.48%	16.06%	1.66%	21.99%

Table 7: The Comparative Static Analysis of the Ad Valorem Tax Rate under a Non-Cooperative Fishing Regime, when Tuna Vessels are Locally Owned

Parameters & Variables	$\boldsymbol{\Delta\delta}$ ↑	$\boldsymbol{\Delta P}$ ↑	$\boldsymbol{\Delta\sigma_t}$ ↑	$\boldsymbol{\Delta c}$ ↑	$\boldsymbol{\Delta\gamma}$ ↑
Anchovy stock (A)	↓	↓	↑	↓	↑
Tuna Stock $\left(x^{*}\right)$	↓	↓	↓	↑	↑
Tuna Baitfish(A_1)	↑	↑	↓	↑	↓
Anchovy Catch(A_2)	↑	↓	↑	↓	↓
Tuna Catch $\left(h^{*}\right)$	↑	↑	↑	↓	↓
Total Anchovy Catch $(A_1 + A_2)$	↑	↑	↓	↑	↓
Tax $\left(\tau'^{*}\right)$	↓	↓	↑	↓	↓

4.6 Foreign Tuna Fleet Ownership with Continuous Harvest of Baits

The results in the 4th column of Table 6 are for a case where the tuna vessels are foreign owned. Some key findings are worth noting. Firstly, the ad valorem tax is much higher than the rate for the case where the tuna vessels are locally owned. This is because the latter only accounts for the congestion externality, whilst the former mitigates the congestion externality and appropriates rents from fishing tuna beyond normal profits. The reason is that the transfer of rents from foreign tuna vessels to the social planner is non-distortionary. Furthermore, suppose ecosystem damages are associated with bait fishing; then its equilibrium catch must be lower, compared to the counter-factual situation, whilst anchovy landed by artisanal fishers must increase. Finally, if bait fishing is done within short time periods, as an alternative to continuous harvesting, the equilibrium anchovy stock, baitfish and tuna landing will be higher, while the equilibrium artisanal harvest of anchovy will be lower. Moreover, the optimal tax rate will be higher than under the continuous harvest of baitfish.

The comparative static analysis of the tax rate under foreign ownership of the tuna fleet (with continuous harvest of the baitfish) has been presented in Table 8 (and Table 8A in Appendix A). A rise in the price of tuna should be accompanied by a reduction in the ad valorem tax. Note that if the price of tuna increases, a lower proportion is enough to internalize the environmental opportunity cost and to pay the rent due to the resource-rich country, hence the negative relationship between the two variables. Furthermore, the catchability coefficient and the tax rate are positively related, since increased fishing gear efficiency leads to increased fish mortality, all else equal. Finally, from the results, an increased cost per unit of tuna or anchovy fishing effort will make fishing less profitable, in which case the tax should decrease.

Table 8: Comparative Static Analysis of Ad Valorem Tax if Tuna Vessels are Foreign Owned and Bait Fishing is Continuous.

Parameters & Variables	$\boldsymbol{\Delta\delta} \uparrow$	$\boldsymbol{\Delta P} \uparrow$	$\boldsymbol{\Delta\sigma_t} \uparrow$	$\boldsymbol{\Delta c} \uparrow$	$\boldsymbol{\Delta\gamma} \uparrow$
Anchovy stock (A)	↓	–	–	–	↑
Tuna stock $\left(x^*\right)$	↓	↓	↓	↑	–
Tuna baitfish(A_1)	↑	↑	↓	↑	–
Anchovy catch(A_2)	↑	↓	↑	↓	↓
Tuna catch $\left(h^*\right)$	↑	↑	↑	↓	–
Total anchovy catch $(A_1 + A_2)$	↑	–	–	–	↓
Tax $\left(\tau'^*\right)$	↓	↑	↑	↓	↓

5. Concluding Remarks

Small pelagic species, such as anchovy, are vital for livelihoods in developing coastal countries and also are an input (baitfish) for catching tuna. Yet, such species are facing growing threats owing to overcapacity by artisanal fishers and tuna bait boats, which are often foreign owned. The competition for the stock by the two fisheries and the use of destructive fishing gear by tuna bait boats have deepened biological overfishing, which can lead to eventual stock collapse. A typical case is the collapse of sardine fisheries in Ghana in the 1970s. To better appreciate the problem, I have developed a bio-economic model and derived expressions for a Pigouvian tax to mitigate the congestion externality and ecosystem destruction, under some possible scenarios.

The study has found that, if tuna vessels are locally owned, and if bait fishing does not damage the ecosystem, the tax on baitfish catch should decrease in the social discount rate, all else equal. Furthermore, if the tuna fleet is foreign owned, then an ad valorem tax can be employed to ensure that the tuna fisher does not run at a loss. The tax should be higher if the vessels employ destructive fishing techniques but lower if the price of tuna or the cost of catching the baitfish or tuna increases, all else equal.

It is noteworthy that most artisanal fisheries in developing countries are managed as open-access or common pool resources, with some gear restrictions, which has driven small pelagic stocks to the brink of collapse. The competition from tuna bait boats, if not regulated, can spell doom for many small pelagic fisheries in the long run.

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Appendix A

Appendix Table 7A: The Comparative Static Analysis of the Ad Valorem Tax Rate under a Non-Cooperative Fishing Regime, when Tuna Vessels are Locally Owned

Parameters & Variables		$\boldsymbol{\Delta\delta} \uparrow$	$\boldsymbol{\Delta P} \uparrow$	$\boldsymbol{\Delta\sigma_t} \uparrow$	$\boldsymbol{\Delta c} \uparrow$	$\boldsymbol{\Delta\gamma} \uparrow$
c	100	100	100	100	**110**	100
p	0.02	0.02	**0.03**	0.02	0.02	0.02
δ	0.03	**0.05**	0.05	0.05	0.05	0.05
$\alpha; \beta$	1.588558; 0.000008	1.588558; 0.000008	1.588558; 0.000008	1.588558; 0.000008	1.588558; 0.000008	1.588558; 0.000008
$\theta; \varsigma$	28.591; 0.0032	28.591; 0.0032	28.591; 0.0032	28.591; 0.0032	28.591; 0.0032	28.591; 0.0032
σ_a	0.000201462	0.000201462	0.000201462	0.000201462	0.000201462	0.000201462
σ_t	0.00000765	0.00000765	0.00000765	**0.0000765**	0.00000765	0.00000765
k_a	141917.5835	141917.5835	141917.5835	141917.5835	141917.5835	141917.5835
k_t	207526.0296	207526.0296	207526.0296	207526.0296	207526.0296	207526.0296
r_a	1.8	1.8	1.8	1.8	1.8	1.8
r_t	1.52	1.52	1.52	1.52	1.52	1.52
b	0.1	0.1	0.1	0.1	0.1	0.1
γ	0.8	0.8	0.8	0.8	0.8	**1.2**
υ	0.000	0.000	0.000	0.000	0.000	0.000
Anchovy stock (A)	87854.795	87366.99	87705.081	89280.468	87781.038	97791.969
Tuna stock $\left(x^*\right)$	131292.81	130094.32	120341.267	109311.245	133277.048	134960.765
Tuna baits(A_1)	11393.44	11563.31	12094.793	4463.326	11739.586	10128.084
Anchovy catch(A_2)	48848.7	48884.9	48211.2	55142.0	48534.1	44602.5
Tuna catch $\left(h^*\right)$	73308.8	73781.6	76846.9	78634.4	72479.8	71731.1
Total anchovy catch $(A_1 + A_2)$	60242.1	60448.2	60306.0	59605.3	60273.7	54730.6
Tax $\left(\tau'\right)$	5.48%	5.45%	5.47%	5.55%	5.48%	3.91%

Appendix Table 8A: The Comparative Static Analysis of the Ad Valorem Tax Rate under Foreign Tuna Fleets

Parameters & Variables		$\boldsymbol{\Delta\delta}\uparrow$	$\boldsymbol{\Delta P}\uparrow$	$\boldsymbol{\Delta\sigma_t}\uparrow$	$\boldsymbol{\Delta c}\uparrow$	$\boldsymbol{\Delta\gamma}\uparrow$
c	100	100	100	100	**110**	100
p	0.02	0.02	**0.03**	0.02	0.02	0.02
δ	0.03	**0.05**	0.03	0.03	0.03	0.03
$\alpha;\beta$	1.588558; 0.000008	1.588558; 0.000008	1.588558; 0.000008	1.588558; 0.000008	1.588558; 0.000008	1.588558; 0.000008
$\theta;\varsigma$	28.591; 0.0032	28.591; 0.0032	28.591; 0.0032	28.591; 0.0032	28.591; 0.0032	28.591; 0.0032
σ_a	0.000201462	0.000201462	0.000201462	0.000201462	0.000201462	0.000201462
σ_t	0.00000765	0.00000765	0.00000765	**0.0000765**	0.00000765	0.00000765
k_a	141917.5835	141917.5835	141917.5835	141917.5835	141917.5835	141917.5835
k_t	207526.0296	207526.0296	207526.0296	207526.0296	207526.0296	207526.0296
r_a	1.8	1.8	1.8	1.8	1.8	1.8
r_t	1.52	1.52	1.52	1.52	1.52	1.52
b	0.1	0.1	0.1	0.1	0.1	0.1
γ	0.8	0.8	0.8	0.8	0.8	**1.2**
υ	0.000	0.000	0.000	0.000	0.000	0.000
Anchovy stock (A)	90151.933	89715.015	90151.933	90151.933	90151.933	100261.041
Tuna stock $\left(x^*\right)$	145219.973	144359.149	127386.720	112970.091	148607.385	145219.973
Tuna baits (A_1)	7723.602	7776.774	8759.465	3008.840	7877.302	7723.602
Anchovy catch(A_2)	51467.0	51624.2	50431.2	56181.8	51313.3	45249.1
Tuna catch $\left(h^*\right)$	66271.6	66789.0	74772.3	78239.0	64130.4	66271.6
Total anchovy catch (A_1+A_2)	59190.6	59400.9	59190.6	59190.6	59190.6	52972.7
Tax $\left(\tau/^{*}\right)$	16.06%	16.01%	43.75%	72.30%	11.53%	7.11%