Ghanaian Journal of Economics, Vol. 6, December 2018


# Bioeconomics of fisheries management under common pool and territorial use rights regimes

Wisdom Akpalu

United Nations University – World Institute of Development Economics Research (UNU-WIDER), University of Ghana, Legon-Accra, Ghana
E-mail: akpalu@wider.unu.edu
Telephone: +233541886443

**Abstract**

Fish stocks in developing countries typically are managed either as common pool resources by many fishing communities or by individual communities, each of which claims territorial use rights over a fraction of a management area. Due to extraction externalities, each of these two regimes results in an economically inefficient outcome relative to a situation where a social planner manages the entire fishery. We have obtained expressions for a feasible tax on cost of harvest (as opposed to ad valorem tax) that could generate first-best outcomes in static and dynamic settings. The tax rate has been computed for a communally owned fishery using data on artisanal fishing in Ghana. Furthermore, in the absence of such a tax, an expression has been developed based on the relationship between the size of the carrying capacity of the fish stock per fishing community and the number of communities involved in harvesting the stock, to determine which regime is better than the other.

**Keywords:** *Common pool resources; Territorial use rights; Fishing Policy.*

**JEL codes:** *Q27, Q22, C61, H21.*

## 1. Introduction

Renewable resources such as wild fish stocks self-generate and could potentially provide perpetual flows of goods and services if the rate of usage is kept at sustainable levels (Clark, 1973). In the world's poorest regions, where 65-75 percent of people live in rural areas, natural resources are communally owned, with access usually restricted to individuals with historic rights (Dasgupta, 1982; 2005). Gordon (1954) and Hardin (1968) indicated that unregulated commons are subject to overuse. This is because the appropriation cost a user incurs is less than what it ideally ought to be, thereby triggering a race to the bottom. The result is rent dissipation, a situation termed "the tragedy of the commons," as "freedom in the commons brings ruin to all" (Hardin, 1968). Hardin (1968) indicated that it is in the interest of society to restrict usage either by fencing or clearly defining use rights. However, Bromley (1992) and several other studies (see e.g. Wade, 1987; Ostrom, 1992) found that, if a renewable resource is managed as common property, access is restricted to members of the community, which makes it possible to avoid the tragedy of the commons. According to Ostrom (2010), there exist multiple cases where resource users were successful in organizing themselves, which challenges the presumption that it is impossible for resource users to solve their own problems of overuse. In addition, Bromley (1991) noted that introduction of state property regimes to address resource degradation in developing countries weakens local customary regimes.

However, in the absence of any restriction on inputs, if private cost of harvest is low relative to the number of users of the resource, the aggregate catch level may deviate from the first-best costless cooperative solution due to congestion externalities. As a result, managing a renewable resource as a common property could potentially result in an economically inefficient outcome. An alternative management strategy of a renewable resource (e.g., marine fish stock) is to zone the area occupied by the resource (e.g., the ocean) and grant territorial use rights (TUR) to each beneficiary community that has socially integrating forces (Defeo and Castilla, 2005; Wyman, 2008; and Costello and Kaffine, 2010)[1]. The TUR is usually accompanied by responsibilities relating to exercising rights of use, exclusion, and proper management of the resource base (Panayotou, 1984; Martin, 1994). However, the character of typical growth functions (e.g., logistics growth function) of fish stocks commonly used in bioeconomic modeling exhibit subadditivity properties, implying that dividing the management area (i.e., giving up the benefits of carrying capacity at a larger scale) results in suboptimal *aggregate* economic surplus. Thus, resource use externalities make it economically inefficient to divide them into private

---

[1]. *TUR in fishing is feasible if the species involved have limited mobility, which happens to be the case for small pelagic species such as sardines and anchovies, considered in this study (Palumbi, 2004; and Castilla, 2010). Within the context of this paper, TUR is characterized by community-based sole ownership.*

parcels, even if each parcel is managed as a community-based sole owner resource (see Dasgupta and Heal, 1979; Dasgupta, 1982).

This study seeks (1) an optimal tax on the cost of harvest, at the level necessary to internalize the congestion externality if a renewable natural capital is communally owned; and (2) an optimal tax that regulates harvest to accommodate overharvesting due to divisibility of the management area. Among other contributions, the manuscript extends the work of Dasgupta (2005), which derives an expression for an ad valorem tax for a common pool resource. Such a tax is costly or impossible to implement due to incomplete and imperfect output markets in developing countries. In addition, there is overwhelming evidence in support of communities charging user fees to regulate the rate of extraction in Common Pool Resources (CPRs) (see e.g., Chopra and Dasgupta, 2002; Dasgupta, 2005; Chou 2010).

Our study reveals that the tax under communal ownership depends on (cooperative) harvest elasticity of effort and on the number of resource users. Furthermore, supposing that non-economic factors such as political forces render the implementation of such an optimal tax impossible, we have shown that it is possible to compare the two suboptimal regimes in order to determine which one is better. The decision rule regarding which of the two options is better in both static and dynamic settings rests on the relationship between the size of the carrying capacity of the stock and the number of communities. To the best of our knowledge, this is the first attempt at comparing these two potentially suboptimal management regimes to obtain a second-best outcome. Using data on an artisanal marine fishery from Ghana, the optimal tax is illustrated.

The remainder of the paper is organized as follows. Section 2 introduces the modeling strategy. The timeless (static) theoretical model is developed in Section 3, followed by a dynamic model in Section 4. The last section (i.e., Section 5) highlights the conclusions of the paper.

## 2. The model

Two sets of models are presented: a static (timeless) model and a dynamic model that accounts for time discounting. For each set of models, equilibrium catch conditions under CPR and TUR fishing are compared with benchmark best solutions and optimal taxes that could guarantee first-best outcomes. Furthermore, if it is (say, politically) infeasible to impose such taxes, a second-best solution is sought by comparing the suboptimal outcomes under the CPR and TUR fishing. We begin by presenting the static model, followed by the dynamic one.

## *2.1. The Static (Timeless) Model*

Suppose a biomass ($x$) of a renewable resource, e.g., fish stock grows according to the logistic function, $g(x,K)$; where $K$ is a constant environmental carrying capacity and $g_{xx}(g) < 0$.[2] Assume there is human predation and define a Schaefer harvest function as $H(x, E)$ (with $H_x(.) > 0$, $H_E(g) > 0$ and $H_{Ex}(g) > 0$), where $E$ signifies effort, and harvest is concave in both arguments. Let the stock dynamic equation be:

$$\dot{x} = g\left(x,K\right) - H(x,E) \tag{1}$$

where $\dot{x} = \frac{dx}{dt}$. In steady state, $\dot{x} = 0$ and equation (1) becomes

$$H(x,E) = g(x,K) \Rightarrow x = x(E,K) \tag{2}$$

If the value of $x$ (from equation 2) is substituted into the harvest function (i.e. $H(x,E)$, an equilibrium harvest function (i.e., yield function) denoted by equation (3) is obtained.

$$Y = Y\left(E,K\right) \ , \tag{3}$$

where $Y_E(\cdot) > 0$ and $Y_{EE}(\cdot) > 0$.

### *2.1.1. Fish stock as a common-pool resource (CPR) under Static Optimization*

Now, following Cheung (1970) and Dasgupta (2005), suppose the stock is exploited as a common-pool resource and each community representative obtains a fraction of the value of the communities' total yield defined by the expression $s_i\left(E_i,K\right) = pY_i = \frac{E_i}{E}pY\left(E,K\right)$, where $i$ $(= 1, 2, \ldots, n)$ is a community index, $E = \sum_{i=1}^{n} E_i$, $Y = \sum_{i=1}^{n} Y_i$ and $p$ is the price per kilogram of fish, which is normalized to one hereafter.[3] Furthermore, let $c$ be cost per unit effort. The instantaneous net benefit of community $i$ is:

$$\pi_i\left(E_i,K\right) = s_i\left(E_i,K\right) - cE_i = \frac{E_i}{E}Y\left(E,K\right) - cE_i \tag{4}$$

If equation (4) is maximized with respect to $E_i$ and symmetry is assumed (i.e. $\sum_{i=1}^{n} E_i = nE_i$), we have the following Nash equilibrium solution:

$$\frac{d\pi_i\left(E_i,K\right)}{dE_i} = 0 \Rightarrow \left(1 - \frac{1}{n}\right)\frac{Y\left(E,K\right)}{E} + \left(\frac{1}{n}\right)Y'\left(E,K\right) = c \ , \tag{5}$$

---

[2] *Note that $g_{xx}(\cdot)$ denotes the second-order derivative of the growth function with respect to x. Similar notation is used for other derivatives in this paper.*

[3] *Although individual fishers within a community could be inherently heterogeneous, we model the behavior of a representative or generic fisher within each community, but different across communities, in order to avoid the complexities involved in dealing with individual heterogeneity within and across communities. The assumption of a representative agent is not uncommon in the literature (see, e.g., Champetier et al. 2010; Smith and Crowder, 2011). Notably, the parameters in the model represent averages over the population of fishermen in each community (Smith and Crowder, 2011).*

where $Y'(E,K) = dY(E,K)/dE$. Equation (5) stipulates that, in equilibrium, marginal benefit from investing an extra unit of effort must equate the cost per unit effort. Interestingly, the benefit is a weighted average of marginal revenue plus average revenue, with the weight defined by the number of communities. If the fishery is managed by a single community (i.e., $n = 1$), the equilibrium condition becomes the desirable profit maximizing condition, i.e., marginal revenue equals marginal/average cost ($dY(E,K)/dE=c\backslash_{E=E^*}$).

On the other hand, if the resource is managed as open-access (i.e., $n \to \infty$) then the condition is: average revenue equals average cost (i.e., $Y(E_\infty,K)/E_\infty=c$). Note that, if the functional forms of the harvest and growth functions are known, an equilibrium effort level corresponding to equation (5) could be solved for, i.e., $E_i = E_i(n,k_i)$, where $K = \sum_{i=1}^{n} k_i$ or $K = nk$ if symmetry is assumed.[4]

*2.1.1a. CPR and Optimal Tax under Static Optimization*

In this section, we seek an optimal tax on cost per unit effort (i.e., $c$) that guarantees maximum economic surplus from the fishery. In situations where prices of output vary considerably depending on the quality of output (i.e., size and species of fish caught), taxes on cost of effort (e.g. taxes on premixed fuel or fishing license fees) seem desirable. Let the tax rate be $\tau$ so that the cost per unit effort is scaled up by $1 + \tau$. With the tax, equation (5) becomes:

$$\left(1-\frac{1}{n}\right)\frac{Y(E,K)}{E}+\left(\frac{1}{n}\right)Y'(E,K)=c(1+\tau) \tag{6}$$

But we know that maximum benefit is obtained if $n = 1$, $Y'(E^*,K) = c$ and $E^* = E(K,c)$. To obtain the expression of the tax that generates the first-best outcome (i.e., the outcome corresponding to $n = 1$), equation 6 becomes:

$$\left(1-\frac{1}{n}\right)\frac{Y(.)/E^*}{Y'(.)}+\frac{1}{n}=(1+\tau) \tag{7}$$

Let $\frac{Y(.)/E^*}{Y'(.)}=\frac{1}{\varepsilon}$, where $\varepsilon$ is yield elasticity of effort evaluated at $E = E^*$ (i.e., effort level corresponding to maximum economic yield). Because $Y_{EE}(\cdot) < 0$ and $Y(\cdot)/E^* > Y'(\cdot)$ at $E = E^* > 0$, it follows that $\varepsilon \in (0,1)$, if $Y(\cdot) > 0$ and $Y_E(\cdot) > 0$. The optimal tax (i.e., $\tau$) expression from equation (7) is

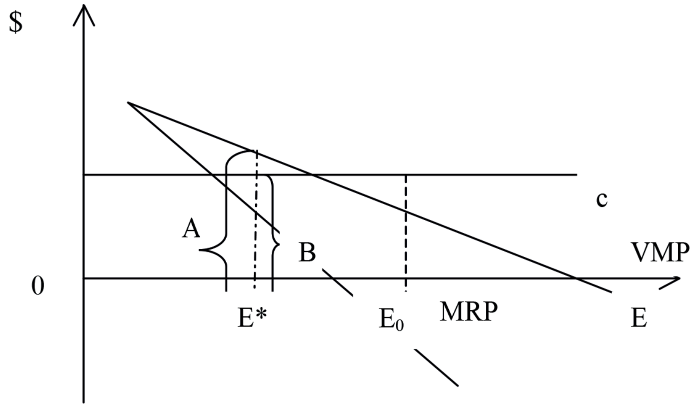
$$\tau=\left(1-\frac{1}{n}\right)\frac{1}{\varepsilon}-\left(1-\frac{1}{n}\right)=\left(\frac{n-1}{n}\right)\left(\frac{1}{\varepsilon}-1\right) \tag{8}$$

---

[4] *The assumption that carrying capacity is dependent on the size of management area or patches is common in the fisheries literature (see, e.g., Bensenane et al., 2013; Sanchirico, 2005). The community specific carrying capacity $k_i$ can be perceived as community i's share of the total fish biomass.*

If the entire resource is managed by a social planner (i.e., if $n = 1$) there is no need for a tax on cost per unit effort (i.e., $\tau = 0$). On the other hand, if the resource is open-access (i.e., $n = \infty$), then $\tau \approx \left(\frac{1}{\varepsilon} - 1\right)$. Figure 1 illustrates how the yield elasticity is obtained.

**Fig. 1. Illustration of yield elasticity of effort ($\left(\frac{B}{A}\right) = \varepsilon$)**




The horizontal line represents the cost per unit effort (i.e., $c$); $Y(.)/E^* = VMR$ (i.e., the Value of Marginal Productivity) and $Y'(.)$ (i.e., Marginal Revenue Product). The effort level corresponding to maximum economic yield is $E^*$. The elasticity is therefore calculated as $\varepsilon = \frac{B}{A}$. Note that, if the cost curve shifts down (up), the elasticity coefficient decreases (increases). Thus the tax accounts for the externality and the tax increases if the gap between marginal social benefit and marginal private benefit increases.[5]

*2.1.1b. Properties of the Optimal Tax*

Taking the partial derivative of the tax expression with respect to the number of resource users and the yield elasticity of effort, the following expressions are obtained:

$$\Delta_n \tau(n) = \tau(n+1) - \tau(n) = \left(\frac{1-\varepsilon}{\varepsilon}\right)\left(\frac{1}{n(n+1)}\right) > 0 \qquad (9)$$

$$\frac{\partial \tau}{\partial \varepsilon} = -\left(\frac{n-1}{n}\right)\left(\frac{1}{\varepsilon^2}\right) < 0 \qquad (10)$$

5. *Suppose the growth function is logistic (i.e., g(.) = $rx(1-xK^{-1})$ and the harvest function is of a Schaefer-type (i.e., $H = \sigma xE$). Then the tax expression is $\tau = 0.5(p\sigma Kc^{-1}-1)(n-1)n^{-1}$. The use of the logistic growth function is based on the assumption that the existing fish stock is greater than the minimum viable stock level.*

where $\Delta_n$ is the discrete derivative of the tax function with respect to *n*. Equation (9) implies that the optimal tax must increase if the number of the beneficiaries from the resource increases, due to the congestion externality. Equation (10) requires some elucidation. The elasticity simply measures the ratio of the marginal yield to the average yield if the economic benefit from the resource is at maximum. The ratio (or elasticity) gets smaller as the maximum economic yield approaches the maximum sustainable yield (i.e., the yield level at which $dY(E,K)/dE = 0$). As a result, if the elasticity increases (decreases), the tax rate necessary to maximize total economic surplus should decrease (increase). As illustrated in Fig. 1, an increase in cost per unit effort, for example, will increase the elasticity coefficient and thereby reduce the tax rate.

### *2.1.2. Zoning the Fishing Area under Static Optimization*

In a bid to regulate overexploitation of fishery resources and generate maximum economic surplus in developing countries, fisheries managers grant communities territorial use rights over the resources within given management areas. It is common for a fishing community that is assigned TUR to have a leader (e.g., the chief fisherman in Ghana) who oversees the management of the fishery and enforces harvest rules. Thus, we assume that, under the TUR, the management of the fishery mimics community-based sole owner management. Furthermore, let the carrying capacity of the stock (i.e., $k_i$) be defined by the size of the management area of the community. The stock dynamic equation within the management area *i* is

$$\dot{x}_i = g_i\left(x_i, k_i\right) - h_i(x_i, E_i) + d\left(\frac{X_{-i}}{K_{-i}} - \frac{x_i}{k_i}\right) \tag{11}$$

where, e.g., $d$ is a parameter for dispersion of species in community $i$ ; $X_{-i} = \sum_{j=1}^{n} x_j$ , $\forall j \neq i$ , $\sum_{i=1}^{n} k_i = K$ ; and $K_{-i} = \sum_{j=1}^{n} k_j$ , $\forall j \neq i$ . Note that $\frac{x_i}{k_i}$ is the density of the stock in the management area of community *i*. For analytical convenience, we assume that the stock is made up of pelagic species that are uniformly mixed so that the last term in the parentheses of equation (11) is zero. Furthermore assume that the growth function of the stock is logistic. The corresponding yield equation is $Y_i = h(E_i,K_i)$. The instantaneous net benefit function for each symmetric community is:

$$\pi_i(E_i, k_i) = h\left(E_i, k_i\right) - cE_i \tag{12}$$

where $h(E_i,K_i)$ is yield. Maximizing equation (12) with respect to effort gives:

$$\frac{d\pi\left(E_i,k_i\right)}{dE_i} = \frac{dh\left(E_i,k_i\right)}{dE_i} - c = 0 \Rightarrow \frac{dh\left(E_i,k_i\right)}{dE_i} = c \Rightarrow E_i^{**} = E_i^{/}\left(k_i, c\right) \tag{13}$$

Equation (13) indicates that, in equilibrium, marginal revenue (i.e., $dh(E_i,K_i)/dE_i$) equals marginal cost (i.e., $c$) of harvest at each fishing zone.

### *2.1.2a. TUR and Optimal Tax under Static Optimization*

Due to the subadditivity property of logistic growth functions, it follows that $\sum_{i=1}^{n} h_i(E_i,k_i) \geq H(E,K)$ for all $E \geq 0$.[6] This implies the aggregate harvest of all the zones may exceed the most economically profitable levels of harvest if carrying capacity is proxied by the size of the management area of each zone. As a result, an economic incentive may be needed to regulate harvest if more than one zone exists. The corresponding expression for the optimal tax on cost per unit effort is:

$$nh_i\left(c(1+\tau),k_i\right) = H(c,K) \tag{14}$$

where $H(c,K)$ is the socially desirable yield. Using a logistic growth function and Schaefer harvest function, the solution for the tax yields the following specific expression:

$$\tau = \tau(n,c,k) = \sigma k(n-1)c^{-1} \tag{15}$$

It can be verified from (15) that $\frac{\partial \tau}{\partial c} < 0$, $\frac{\partial \tau}{\partial \sigma} > 0$ and $\Delta_n \tau(n) > 0$.

### *2.1.3. Timeless (static) second best condition*

From the preceding discussion, both CPR management and granting territorial use rights to communities could potentially result in inefficient outcomes if policy instruments are not employed. In this section, the conditions under which one outcome is better than the other is investigated by comparing the economic surpluses in the two situations. Let the net economic benefit from the CPR (i.e.,$\pi(E_i(n,k_i))$) equal that of TUR management (i.e., $\pi(E_i^{/}(k_i))$), i.e.,

$$\pi\left(E_i\left(n,k_i\right)\right) = \pi\left(E_i^{/}\left(k_i\right)\right) \Rightarrow k_i = k_i(n) \tag{16}$$

Equation (16) stipulates an equilibrium relationship between the carrying capacity of each community and the number of fishers required to guarantee equal economic surplus under the two outcomes. A deviation from this equilibrium relationship implies that one outcome must be preferred. To clarify this condition, some specific functional forms are adapted for convenience. The harvest and growth functions are $H(x,E) = \sigma xE$ and $g(x,K) = rx(1\text{-}xK^{-1})$, respectively. The corresponding equilibrium net benefit functions for the CPR and TUR are (17) and (18) respectively.

$$\pi\left(E_i^*\right) = \sigma n k_i E_i^*\left(1-\frac{\sigma}{r}nE_i^*\right) - cE_i^* \tag{17}$$

---

[6] *Suppose there is no human predation and* $i = 1,2$. *In steady state,* $x = (x_1 + x_2) = (k_1 + k_2) = K$. *On the other hand, if there is human predation,* $x_1 + x_2 = k_1\left(1-\frac{\sigma}{r}E_1\right) + k_2\left(1-\frac{\sigma}{r}E_2\right) \geq x = (k_1+k_2)\left(1-\frac{\sigma}{r}(E_1+E_2)\right)$ $\forall\ E \geq 0$.

$$\pi(E_i^{**}) = \sigma k_i E_i^{**}\left(1-\frac{\sigma}{r}E_i^{**}\right) - cE_i^{**} \tag{18}$$

The equilibrium relationship between the number of communities ($n$) and the carrying capacity ($k_i$) is established by equating equation (17) to (18). Thus

$$\sigma n k_i E_i^{*}\left(1-\frac{\sigma}{r}nE_i^{*}\right) - cE_i^{*} = \sigma k_i E_i^{**}\left(1-\frac{\sigma}{r}E_i^{**}\right) - cE_i^{**} \tag{19}$$

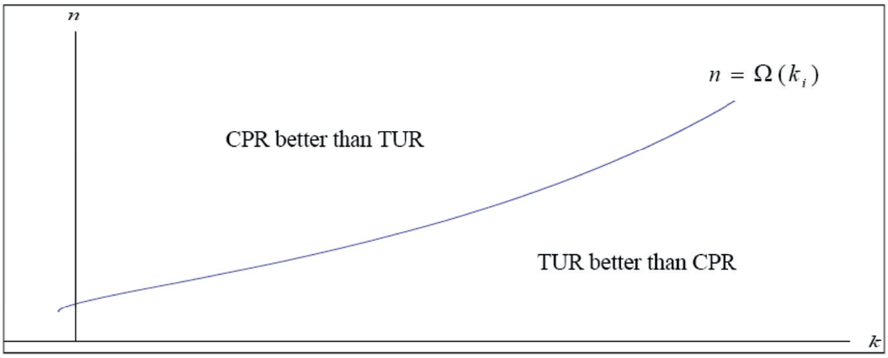
which generates

$$n \in \{\Omega(k_i), 1\} \tag{20}$$

where $\Omega(k) = \dfrac{\left(10ck\sigma + k^2\sigma^2 - 7c^2\right)^{1/2} + 6ck\sigma + k^2\sigma^2 - 3c^2}{2(c-\sigma k)^2}$ .

As expected, there are multiple equilibria, of which $n = 1$ is one of the two. If the social planner of one community manages the entire fishery on behalf of the community, the outcome will generate the maximum economic surplus. On the other hand, if there is more than one community (i.e., if $n > 1$ ), then CPR is better (worse) than TUR management if $n > \Omega(k)(n < \Omega(k))$. The function $n = \Omega(k))$ , which defines the situation of indifference, is graphed below.

**Figure 2. The equilibrium relationship between the number of fishing communities (*n*) and carrying capacity per capita (*k*)**




From the figure, as the number of communities increases, the carrying capacity for each community necessary to ensure that the two management regimes produce equivalent economic benefits must also increase. Thus, for any given level of carrying capacity attributable to each community, if the number of communities lies below the indifference line, then territorial use right (TUR) is better that CPR. Conversely, if, for any number of communities, the carrying capacity per capita lies above the indifference line, then CPR is a better management regime.

### 2.2. The dynamic model

The preceding discussions are based on static equilibrium analysis with no provision for discounting of future costs and benefits. In this section, a dynamic version of the model is presented. Suppose future benefits and costs are discounted at a rate $\sigma > 0$ by each community.[7] The value function of the social planner who manages the entire fishery is equation (21) and the stock dynamic equation is (22).

$$V(x,H) = \max_H \int_0^\infty \left( pH - c(x)H \right) e^{-\delta t} dt \tag{21}$$

$$\dot{x} = rx\left(1 - \frac{x}{K}\right) - H \tag{22}$$

The corresponding current value Hamiltonian of the program is

$$Z(x,H,\mu) = \left(pH - c(x)H\right) + \mu\left(rx\left(1 - \frac{x}{K}\right) - H\right) \tag{23}$$

From the maximum principle, assuming an interior solution exists, the first order condition (with respect to the flow variable $H$ ) is

$$\frac{\partial Z(.)}{\partial H} = p - c(x) - \mu = 0 \tag{24}$$

Equation (24) simply stipulates that, in an inter-temporal equilibrium, harvest must be at a level that equates net marginal benefit (i.e., $p$ - $c(x)$) to the scarcity value of the stock (i.e., $\mu$ ). If $p$ - $c(x) > \mu$, harvest must be at its maximum. On the other hand, it must be set to zero if $p$ - $c(x) < \mu$ . The corresponding co-state equation is

$$\dot{\mu} - \delta\mu = -\frac{\partial H(.)}{\partial x} = c_x H - \mu r\left(1 - \frac{2x}{K}\right) \tag{25}$$

Equation (25) implies that, in dynamic equilibrium, the interest earnable on the net marginal benefit from harvesting a kilogram of fish today (i.e., $\delta\mu$) must equate the sum of the capital gain from conserving that kilogram of fish (i.e., $\delta\mu$) and some stock effect (i.e., $-c_x H + \mu r\left(1 - 2xK^{-1}\right)$ ). In steady state, $\dot{x} = \dot{\mu} = 0$, so that (25) and (24) become:

$$\mu = \frac{-c_x H}{\left(\delta - r\left(1 - 2xK^{-1}\right)\right)} \tag{26}$$

$$p - c(x) = \frac{-c_x\left(rx\left(1 - xK^{-1}\right)\right)}{\delta - r\left(1 - 2xK^{-1}\right)} = \frac{-c_x\left(rx\left(1 - xnk^{-1}\right)\right)}{\delta - r\left(1 - 2xnk^{-1}\right)} \tag{27}$$

Note that the social planner's equilibrium stock (i.e., $x^*$ ) is obtainable from equation (27).

---

[7] *Although individuals in each community may have different rates of time preference, we used social or community level discount rate, which we surmise is constant across communities since all the communities are generally considered poor and depend on the same resource.*

Now suppose the stock is harvested as a CPR by $n$ users. Following Maler *et al.* (2003), the optimization program for each community is:

$$V(x,h_i) = \max_{h_i} \int_0^{\infty} \left(p - c(x)\right) h_i e^{-\delta t} dt, \quad i = 1,2,...,n \tag{28}$$

$$\dot{x} = rx\left(1 - \frac{x}{K}\right) - \sum_i^n h_i, \quad H = \sum_i^n h_i \tag{29}$$

The corresponding first order condition from the maximum principle is

$$\frac{\partial Z(.)}{\partial h_i} = p - c(x) - \mu_i = 0, \quad i = 1,2,...,n \tag{30}$$

The shadow value assigned to the resource by each symmetric community is $\mu_i = \frac{\mu}{n}$. The symmetric open-loop Nash equilibrium solution is

$$p - c(x) = \frac{\mu}{n} = \frac{-c_{\mathbf{x}}\left(rx\left(1 - xK^{-1}\right)\right)}{n\left(\delta - r\left(1 - 2xK^{-1}\right)\right)} = \frac{-c_{\mathbf{x}}\left(rx\left(1 - xnk^{-1}\right)\right)}{n\left(\delta - r\left(1 - 2xnk^{-1}\right)\right)} \tag{31}$$

Equation (31) can be solved for the equilibrium stock level (i.e., $x^{**} = x(k, n)$).

*1. CPR and Optimum Tax under Dynamic Optimization*

Now suppose the resource is harvested as a CPR and let a tax be imposed on cost of harvest (i.e., $c(x)(1 + \tau)$) to generate a first-best solution. The equilibrium stock equation corresponding to equation (31) is

$$p - c(x)\left(1 + \tau\right) = \frac{-c_{\mathbf{x}}\left(1 + \tau\right)\left(rx\left(1 - xK^{-1}\right)\right)}{n\left(\delta - r\left(1 - 2xK^{-1}\right)\right)} = \frac{-c_{\mathbf{x}}\left(1 + \tau\right)\left(rx\left(1 - xnk^{-1}\right)\right)}{n\left(\delta - r\left(1 - 2xnk^{-1}\right)\right)} \tag{32}$$

or

$$\frac{n\left(p - c(x)\left(1 + \tau\right)\right)}{\left(1 + \tau\right)} = \frac{-c_{\mathbf{x}}\left(rx\left(1 - xnk^{-1}\right)\right)}{\left(\delta - r\left(1 - 2xnk^{-1}\right)\right)}$$

Using equation (31) in (32) gives the following expression for the tax.[8]

$$\tau = \frac{p - c\left(x^*\right)}{{}^{p}\!/\!_{(n-1)} + c\left(x^*\right)} \tag{33}$$

A comparative static analysis indicates the tax must be increasing in the number of communities and the price of fish but decreasing in the social discount rate (i.e., $\Delta_n \tau(n) > 0$, $\frac{\partial \tau}{\partial p} > 0$, and $\frac{\partial \tau}{\partial \delta} < 0$).

[8] *If the specific functional forms are used, the expression for the tax is*

$$\tau = \frac{\left(kpr\sigma\delta + \left(8ckpr\sigma\delta + \left(\left(cr + kp(r-\delta)\sigma\right)^2\right)^{0.5} - 3cr\right)(n-1)}{cr\left(3 - 4n\right) - kpr\sigma\delta + \left(8ckpr\sigma\delta + \left(\left(cr + kp(r-\delta)\sigma\right)^2\right)^{0.5}}$$

Thus, in order to obtain the maximum benefit from the fishery, the tax rate must increase if the number of communities increases. Furthermore, if the price of fish increases, more fish could be caught, so the tax rate must increase to regulate the catch. Finally, if the society is impatient or uncertain about the future, then more fish should be harvested now, hence the tax rate must be reduced. Recent studies have found a positive relationship between discount rates and catch rates (see e.g. Akpalu, 2008, 2011).

*2. TUR and Optimal Tax Under Dynamic Optimization*

If the fishery is zoned and tax is imposed on cost of harvest, the equilibrium condition corresponding to equation (32) is

$$p - c(x)(1+\tau) = \frac{-c_x(1+\tau)\left(rx\left(1-xk^{-1}\right)\right)}{\delta - r\left(1-2xk^{-1}\right)} \tag{34}$$

Using equation (31) in (34) and solving for the optimal tax gives[9]:

$$\tau = 1 - \frac{p}{np + \left(1 - \frac{1}{n}\right)c(x^*)} \tag{35}$$

Again, the tax expression indicates a zero tax rate if the resource is managed by a single community representative (i.e., $\tau = 0$ if $n = 0$). In addition, in the absence of a tax, the corresponding equilibrium harvest is denoted as $x^{**}(k, n)$.

*3. The second-best solution for the dynamic specification*

In the absence of the economic policy instruments (i.e., the optimal tax), the equilibrium harvest conditions have been equated to obtain an expression for the relationship between the number of resource users and the size of the carrying capacity per capita. As noted earlier, if this condition does not hold, one of the two regimes is preferred. Equating the two functions, we have

$$n\left(p - c\left(x^{**}(k,n)\right)\right) = p - c\left(x^{*}(k,n)\right) \tag{36}$$

Using the specific functional forms and solving for $n$ in equation (36) gives the plot in Figure 3.

---

9. *The specific value of the tax is*

$$\tau = \left(1 - \frac{1}{n - \frac{4c(n-1)r}{n\left(kp\sigma\delta - kpr\sigma - cr + \left(8ckpr\sigma\delta + \left((cr + kp(r-\delta)\sigma\right)^2\right)^{0.5}\right)}}\right)$$

**Figure 3. The dynamic equilibrium relationship between the number of fishing communities (n) and carrying capacity per capita (k) for low and high discount rate.**

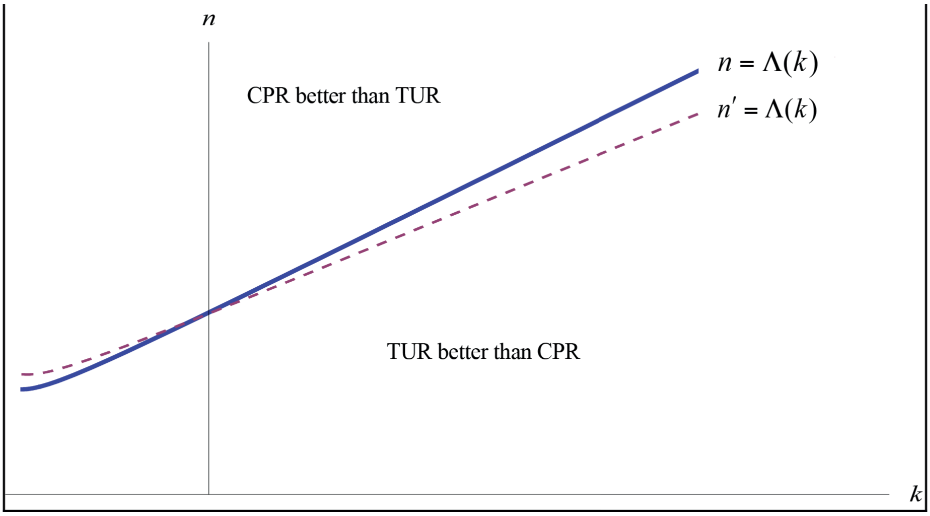



Figure 3, which is like Fig. 2, also indicates that the relationship between the number of fishers and the carrying capacity that generates the same net benefit under the two regimes are positively related. The dashed and thick lines indicate the relationship between the two variables for high and low discount rates respectively. Thus, for any level of carrying capacity per capita, if the number of communities lies above the indifference line, then CPR is better than TUR. Most importantly, a higher discount rate favors the management of the fishery as a CPR.

## 3. Empirical Illustration of the Optimal Taxes

To empirically illustrate the optimal taxes under CPR, data on artisanal fisheries in Ghana is used to compute the yield function and the optimal effort. The nation's capture fishery stocks targeted by artisanal fishers are generally managed as unregulated common pool resources (Akpalu, 2008). There are 185 fishing communities with a total of 11, 213 canoes and 124, 219 fishers along the country's coastline of 550km. The marine fish resources are classified as small pelagic, large pelagic (i.e., mainly tunas), demersal, and mollusc and crustaceans. The artisanal fishery sector which dominates in terms of fleets (64%) and catch volumes (70-80%) targets small pelagic species such as sardine, grunt, ilisha, threadfin, and mackerel (MOFA, 2004). The sector has undergone considerable changes, including improvement in artisanal fishing gear, introduction of outboard motors, and improvement in fish processing and storage techniques, which have led to overexploitation of stocks

(Koranteng, 1992; Akpalu, 2008). Each fishing village or community has an elected fisher, usually called Chief Fisherman, who oversees fishing activities within the fishing community. He is usually granted the power to implement fishing laws and regulations, to resolve fishing-related conflicts, and to punish violators of the fishing laws and regulations. The data for the empirical illustration was obtained from the marine fisheries research division (MFRD) at Tema, Ghana. It is aggregated monthly data on artisanal catch and effort of the 185 fishing communities along the coast of Ghana between 2000 and 2006. The descriptive statistics are presented in Table 1.

**Table 1. Descriptive Statistics of Catch and Effort Data (2000-2006)**

| Variable | # of obs | Mean | SD |
|---|---|---|---|
| Catch (in kg) (for 185 communities) | 84 | 19942.97 | 10998.31 |
| Fishing effort (# of Trips) (for 185 communities) | 84 | 84683.93 | 19796.86 |

*Source: Secondary Data from the marine fisheries research division (MFRD), Tema, Ghana.*

The mean monthly catch for the entire 185 communities is 19,943kg, with a very high standard deviation (10998.31). The average number of trips, which is a proxy for effort, is about 85,000 per month.

The yield function estimated is $Y = (\sigma K)E - (\sigma^2 K r^{-1})E^2$, which is a quadratic function without an intercept. The ordinary least square regression results are presented in Table 2. The F-statistics indicates that the line is a good fit. The coefficients of effort and effort-squared are significant at the 1 percent level.

**Table 2. Estimation of Equilibrium Yield Function**

| Variable | Coefficient |
|---|---|
| Fishing effort (# of Trips) | 0.439 (0.063)*** |
| Fishing effort squared (# of Trips squared) | -0.0000023 (0.000000582)*** |
| F( 2, 82) = 211.50 (Prob > 0.00 ) | |

*Notes: Robust standard errors are in parentheses. *** significant at 1%. The coefficient of "Fishing effort squared" and its standard error are very small and hence may be sensitive to the type and memory of the software used for the computation. As a result, the value may be considered as an approximation.*

*Source: Computed by Author*

From the regression results, the yield function is $0.439E$ - $0.0000023E^2$ and the corresponding condition for maximum economic benefit from the fishery (i.e., $dY(E,K)/dE = c\big|_{E=E^*}$ ) is $pY'(E,K) = p\sigma K\left(1 - \frac{2\sigma}{r}E\right) = p\left(0.439 - 0.0000046E^*\right) = c$.

### *3.1. CPR and Estimated Optimal Tax under Static Optimization*

Estimation of optimal effort requires values for cost per unit effort and price of fish. Based on the median running cost of fishing vessels in Ghana and average revenue from catch reported in Brinson *et al*. (2009), figures of $c$ = \$95.88US and $p$ = \$264.36US have been used. The optimal effort is calculated to be $E^*$ = 16589.73 and the corresponding elasticity is $\varepsilon$ = 0.90481. Currently there are 185 fishing communities in Ghana, implying the optimum tax rate is:

$$\tau = \left(\frac{n-1}{n}\right)\left(\frac{1-\varepsilon}{\varepsilon}\right) = \left(\frac{185-1}{185}\right)\left(\frac{1-0.90481}{0.90481}\right) = 0.105 \tag{37}$$

Thus, because the entire artisanal fishery is managed as an unregulated common pool resource by the 185 communities, a tax rate of 10.5% on cost per unit effort could generate the optimal economic benefit from the fishery. On the other hand, if $n$ is defined as the number of fishers, then it equals 124,000 and the tax rate is approximately 10.52%. Notably, the two values are very close because (185-1)/185≈(124,000-1)/124,000≈1. In Ghana, premixed fuels constitute a significant portion of fishing cost and hence potentially could be taxed to regulate harvest.

$$\tau = \frac{(n-1)\left(Kp\sigma(r-\delta)-3cr+\left(8cKpr\sigma\delta+\left((cr+Kp(r-\delta)\sigma)^2\right)^{0.5}\right)\right)}{cr(4n-3)+Kp\sigma(r-\delta)+\left(8cKpr\sigma\delta+\left((cr+Kp(r-\delta)\sigma)^2\right)^{0.5}\right)} \tag{38}$$

The results from the simulations are presented in Table 3. The base line optimal tax value is 13.9%. The tax rate must increase if the price of fish or the catchability coefficient increases, but must decrease if cost per unit of effort or social discount rate increases.

**Table 3. Estimation of Equilibrium Yield Function**

| *P* | *r* | *c* | *K* | *δ* | *σ* | *n* | *tax* (τ) |
|---|---|---|---|---|---|---|---|
| 264 | 1.59 | 96 | 66614.14 | 0.03 | 0.000007 | 185 | 13.88% |
| 264 | 1.59 | 96 | 66614.14 | 0.05 | 0.000007 | 185 | 13.79% |
| 300 | 1.59 | 96 | 66614.14 | 0.03 | 0.000007 | 185 | 22.46% |
| 264 | 1.59 | 100 | 66614.14 | 0.03 | 0.000007 | 185 | 11.36% |
| 264 | 1.59 | 96 | 66614.14 | 0.03 | 0.000008 | 185 | 22.86% |

*Source: Computed by Author*

### *TUR fishing and Optimal Tax under Static Optimization*

If each community had territorial use rights over a given management area, a counterfactual optimal tax rate could be calculated based on equation (15). Note that $\tau = 0$ if $n = 1$. Using $\sigma nk$ = 0.439 and the other parameters values, the tax is

$$\tau \approx \frac{264.36(0.437)}{95.88} = 1.2 \rightarrow 120\%$$

Comparing this rate with the figures obtained for the static and dynamic CPR cases, it is clear a higher tax rate would be required to generate maximum sustainable economic surplus under the TUR management regime. Consequently, the current CPR management regime, though suboptimal, is better than granting TUR to the 185 communities. Thus, the current CPR management regime generates better economic surplus compared to granting TUR.

## 4. Conclusion

A sizeable proportion of the world's poor in rural areas depend on renewable natural capital. The resources are usually communally owned, and access is based on historical rights. However, in the absence of adequate rules of appropriation, such resources are typically overused. An alternative management strategy has been granting territorial use rights (TUR) to each community. However, if the growth function of the stock is logistic, then parceling the carrying capacity into bits is also economically inefficient. Thus, in principle, each of these two regimes results in inefficient outcomes relative to a costless cooperative optimum.

We have obtained an expression for a tax rate necessary to internalize the resource use externality when the resource is managed communally, as well as a tax rate to accommodate the divisibility externality for stocks that generate first-best outcomes. The tax rate on a communally owned fishery, which has been illustrated using data on artisanal fishing in Ghana, is decreasing in harvest elasticity of effort and increasing in the number of resource users. Furthermore, in the absence of such a tax, an expression has been developed based on the relationship between the size of the carrying capacity of the fish stock within each community and the number of communities involved in harvesting the stock to determine which regime is better than the other.

## About the author

**Wisdom Akpalu** is Associate Professor of Economics and a Research Fellow at the United Nations University – World Institute for Development Economics Research (UNU-WIDER). He is the current president of the African Association of Environmental and Resource Economists (AFAERE). His research interests are within the field of natural resource economics and social economics. He has several publications in reputable journals and is an active reviewer for many journals.

## Acknowledgements

I would also like to thank David Starret, Marty Luckert, Edwin Muchapondwa, and Jesper Stage for their comments. Moreover, I would like to express my sincere gratitude to the Center for Environmental Economics and Policy in Africa (CEEPA) for fully funding this research project.

## References


Akpalu, W. (2011). Determinants of noncompliance with light attraction regulation among inshore fishers in Ghana. *Journal of Socio-Economics*, 40(2), pp. 172-177.

Akpalu, W. (2008). Fishing Regulation, Individual Discount Rate and Fisherman behavior in a Developing Country Fishery. *Environment and Development Economics*, 13, pp. 591-606.

Bensenane, M., Moussaoui, A. and Auger P. (2013). On the Optimal Size of Marine Reserves. *Acta Biotheoretica*, 61, pp. 109–118.

Brinson, A. A., Die, D. J., Bannerman, P. O. and Diatta, Y. (2009). Socioeconomic performance of West African Fleets that target Atlantic billfish. *Fisheries Research*, 99 (2009), pp. 55–62.

Bromley, D. (1991). Environment and Economy: Property Rights and Public Policy. Blackwell, Cambridge.

Bromley, D. (1992). Making the Commons Work: Theory, Practice, and Policy. Institute for Contemporary Studies Press, San Francisco.

Castilla, J. C. (2010). Fisheries in Chile: Small Pelagics, Management, Rights, and Sea Zoning. *Bulletin of Marine Science*, 86(2), pp. 221–234.

Champetier, A., Sumner, D. A. and Wilen, J. E. (2010). The Bioeconomics of Honey Bees and Pollination. Working Paper August 2010, University of California, Davis.

Cheung, S. N. S. (1970). The Structure of a Contract and the Theory of a Non-exclusive Resource. *Journal of Law and Economics*, 13(1), pp. 49–70.

Chou, C. (2010). The Local Governance of Common Pool Resources: The Case of Irrigation Water in Cambodia. CDRI Working Paper Series, No. 47. Phnom Penh, CDRI.

Chopra, K. and Dasgupta, P. (2002). Common Pool Resources in India: Evidence, Significance and New Management Initiatives. Mimeo under the UK DFID Project R7973.

Clark, C. W. (1973). The economics of Overexploitation. *Science*, 181, pp. 630-34.

Costello, C. J. and Kaffine, D. (2010). Marine Protected Areas in Spatial Property-Rights Fisheries. *Australian Journal Agricultural and Resource Economics*, 54(3), pp. 321-341.

Dasgupta, P. (2005). Common Property Resources: Economic Analytics. *Economic and Political Weekly*, 16, pp. 1611-1622.

Dasgupta, P. and Heal, G. (1979). Economic Theory and Exhaustible Resources. Cambridge Univertsity Press, Cambridge.

Dasgupta, P. (1982). The Control of Resources. Harvard University Press, Cambridge.

Defeo, O. and Castilla, J. C. (2005). More Than One Bag for the World Fishery Crisis and Keys for Co- Management Successes in Selected Artisinal Latin American Shellfisheries. *Review of Fish Biology and Fisheries*, (15), pp. 265-283.

Gordon, H. S. (1954). The Economic Theory of Common-Property Resources. *Journal of Political Economy*, (62), pp. 124-42.

Hardin, G. (1968). The Tragedy of the Commons. *Science*, 162, pp. 1243-8.

Koranteng, K. A. (1992). The Marine Artisanal Fishery in Ghana, Recent Developments and Implications For Resource Evaluation, A Paper Presented at The World Fisheries Congress, Athens, Greece, May 3-8, 1992.

Martin, I. (1994). Legacy and testament, the story of Columbia River gillnetters. Washington State University Press, Pullman, Washington, USA.

Maler, K.G., Xepapadeas, A. and de Zeeuw, A. (2003). The economics of shallow lakes. *Environmental and Resource Economics*, 26, pp. 603-624.

Ministry of Food and Agriculture (MOFA). (2004). Information on Fisheries in Ghana, The Director of Fisheries, Accra.

Ostrom, E. (1992). Crafting Institutions for Self-Governing Irrigation Systems. Institute for Contemporary Studies Press, San Francisco.

Ostrom, E. (2010). Beyond Markets and States: Polycentric Governance of Complex Economic Systems. *American Economic Review*, 100, pp. 641–672.

Palumbi, S. R. (2004). Marine Reserves and Ocean Neighborhoods: The Spatial Scale of Marine Populations and Their Management. *Annual Review of Environment and Resources*, 29, pp. 31-68.

Panayotou, T. (1984). Territorial use rights in fisheries. United Nations FAO, Rome, Italy. FAO Fish Report No. 289, Supplement.

Sanchirico, J. N. (2005). Additivity properties in metapopulation models: implications for the assessment of marine reserves. *Journal of Environmental Economics and Management*, 49, pp. 1-25.

Smith, M. D. and Crowder, L. B. (2011). Valuing Ecosystem Services with Fishery Rents: A Lumped-Parameter Approach to Hypoxia in the Neuse River Estuary. *Sustainability*, 3, pp. 2229-2267.

Wade, R. (1987). Village Republics: Economic Conditions for Collective Action in South India. Cambridge University Press, Cambridge.

Wyman, K. M. (2008). The property rights challenge in marine fisheries. *Arizona Law Review*, 50 (2), pp. 511–543.