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A Dynamic Model of Mesh Size Regulatory Compliance in Fisheries[1]

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Working Paper Number 123

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A Dynamic Model of Mesh Size Regulatory Compliance in Fisheries[*]

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April 9, 2009

Abstract

The violation of fishing regulations is a criminal activity that leads to depleting fish stock levels across the world. This paper focuses on fishing violations in developing countries. In particular, the paper analyses the use of a fishing net with illegal mesh size in a two regimes, namely a management regime where each community claims a territorial use right over the fishery and a regulated open access regime. This paper employs a dynamic model for fishery crimes that involve time and punishment to analyse the use of a net with illegal mesh size in the different regimes. We found that if the community has territorial use right, the illegal activity in addition to decreasing the intrinsic growth rate and the cost of fishing would increase the community's effective discount rate and consequently result in a much lower equilibrium stock and harvest relative to the situation where the community only use nets with the legal mesh size. Furthermore, under a regulated open access management the equilibrium stock will be lower if a community violates the regulation and the proportionate change in the risk of punishment is higher than the proportionate change in the harvest potential. Moreover, the optimum penalty for violation must be set higher in the open access fishery relative to the complete territorial use right management regime.

Jel Classification: C61; Q21; Q22

Keywords: Crime; Dynamic Model; Fishery; Regulation

1 Introduction

The use of illegal fishing technologies have played a major role in fish stock depletion in many coastal developing countries where monitoring and enforcement of fishery regulations are far from being complete. An illegal fishing technology generates a technological externality that may include the opportunity cost of a mature and more valuable fish in the future. A typical example of such destructive technology is the use of a net with illegal mesh size which has characterised all types of fisheries. According to the FAO (2001), the use of illegal nets, which are highly destructive, is popular in many African countries and is widely used along the coasts, in lagoons, estuaries and rivers. This situation does not differ from prevailing situations in other continents. For example, it has been noted that in a fishery in India, some fishers use stake nets with mesh sizes of less than 5mm in contiguous rows to filter young prawns while the prescribed minimum is 35mm (Srinivasa, 2005).

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Following the seminal paper by Becker (1968), considerable amounts of theoretical and empirical research has been done on violation of fishing regulations. For the theoretical research, see e.g. Sutinen and Anderson (1985), Anderson and Lee (1986), Charles *et al.* (1999), Hatcher (2005), and Chavez and Salgado (2005). The empirical works include Furlong (1991), Hatcher *et al.* (2000) and Hatcher and Gordon (2005). Consistent with Becker's configuration, fishery economists have considered fishing regulations such as closed area and quantity restrictions for which an illegal fisher is a rational self-interested economic agent who maximises a one-period expected utility. Consequently, the fisher engages in illegal fishing if the expected gain from violation outweighs the gain from legal fishing and to the extent that the expected marginal gain equates the expected fine for violating the regulation. A fishery crime that involves the use of an illegal fishing net is committed repeatedly until it is detected, especially in developing countries where a fisher uses one net. Thus, the rational fisher who uses the illegal net weighs the stream of benefits gained from legal fishing with the future expected fine resulting from using the illegal mesh size. This type of criminal activity, involving the repeated use of illegal fishing gear and the potential negative impact of the use of the equipment on a fishery, makes this type of activity a dynamic crime problem and has hardly been investigated in the fishery economics literature (see Akpalu, 2008).

The dynamic nature of the problem requires a dynamic approach in analysis. Like the static model used by Hatcher (2005) and Furlong (1991), the dynamic model presents the framework for analysing the impact of changes in enforcement effort and penalty on the rate of violation. Moreover, employing a dynamic specification that involves time and punishment rather than using a static formulation provides some additional advantages. First, in the dynamic model of crime, the violator weighs the stream of potential net benefits obtainable from fishing illegally. Consequently, if for example a community has a territorial use right over a management area, its *effective discount rate* will determine the levels of exploitation and the optimum stock of the resource. The effective discount rate is the sum of the individual rate of time preference or benefit discount rate and the probability of detection (Davis, 1988). It is noteworthy that the probability of detection depends on the choice of mesh size and enforcement effort of inspectors and a change in any of these two variables will affect both the short-run and optimum harvest and stock levels. Furthermore, since the use of the illegal gear affect the intrinsic growth rate of the stock (Boyd, 1966; Escapa & Prellezo, 2003)[1] the dynamic model makes it possible to determine the impact of the illegal fishing on the growth of the fish stock. Moreover, if the criminal activity is committed repeatedly, the optimal penalty can be evaluated in terms of the probability of detection and the marginal damage resulting from the illegal activity.

Fisheries in many developing countries are managed as either a common property resource where each community claims a territorial use right over a management area or as regulated open access where a community can harvest any quantity of the resource across the entire management area as long as a fishing regulation such as the mesh size regulation is obeyed (Akpalu, 2008). Due to the fact that the use of the illegal fishing gear impacts fish stocks, the optimal stocks have been compared under these regimes. A fine is generally considered costless and remains an important policy instrument for fishery management. We therefore compare the fine under the two regimes. The findings are that the equilibrium fish stock and harvest are much lower if the fisher uses the illegal mesh size relative to a situation where he does not use it under the community use right management regime. The differences in the stock levels stem from both the effect of the use of the illegal net on the growth of the stock and the risk of punishment that scales up the effective discount rate. Also, increasing the risk of punishment increases the optimal level of stock. Under a regulated open access regime, the size of the equilibrium stock will depend on the ratio of elasticity of catchability coefficient that defines the potential benefit from increased intensity of violation to the elasticity of the risk of punishment. The equilibrium stock and harvest levels will be lower if the elasticity of the catchability coefficient is greater than some adjusted elasticity of the hazard rate.

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[1] This specification contrasts with Armstrong and Clark (1997), and Garza-Gil (1998), who assumed that different technologies impact the harvest function, but not the growth function.

Furthermore, with regards to the optimal fines, it has been found that the fine for continuous fishing under regulated open access must be higher than that under community-owned fishery.

The rest of the paper is organised as follows: in the next section (2), the model for territorial use right in a fishery is presented, followed by a regulated open access fishery in section (3). The conclusion of the paper is presented in the last section (4).

2 The Model

In this section, some definitions and assumptions of the model of this paper are presented followed by derivations of some results for the two management regimes that characterise fisheries management in developing countries: where a community has the use right over the fishery within a given management area and a regulated open access regime.

- *Mesh size and stock dynamics*

Suppose that a fishery has pelagic species, such as mackerel, anchovy, sardines etc., which have relatively short periods of maturity and do not fit well into the standard age structure or cohort model of Beverton-Holt (1957). Following Boyd (1966) and Armstrong (1999), suppose that the intrinsic growth rate of the stock depends on an index of the inverse of the mesh size $\alpha \epsilon (0, 1)$ so that the adjusted natural growth function depends on fish biomass x and the mesh size which is a control variable (i.e. $\Lambda(x, \alpha)$ is the growth function)[2]. Since it is expected that decreasing the mesh size may decrease the average size of harvested fish and eventually decrease the number of egg laying fish, the following partial derivatives hold: $\Lambda_x(\bullet) > 0$, $\Lambda_{xx}(\bullet) < 0$ and $\Lambda_\alpha(\bullet) < 0$[3]. The stock evolution or dynamics within a given management area is:

$$\dot{x} = \Lambda(x, \alpha) - h, \tag{1}$$

where $\dot{x} \equiv \frac{dx}{dt}$ and h is harvest which is a control variable[4].

- *The harvest function and gross revenue*

If constant returns to scale is assumed between fishing capacity (i.e., all the inputs used in fishing) and effort $(E(t))$, the Schaefer harvest or production function of the fisher is:

$$h = f(x, E, \alpha) = a(\alpha).E.x, \tag{2}$$

where $a(\alpha)$ is the catchability coefficient function and $a_\alpha > 0$ implying that reducing the mesh size will increase harvest for any given levels of effort and stock. As noted by Mackinson *et al.* (1997), changes in fishing technology impact on the catchability coefficient. The simple Schaefer harvest function is assumed for tractability.

- *Market structure and total revenue from harvest*

As noted earlier, two management regimes are considered in this paper, i.e., a situation where a community has the use right over the fishery within a given management area and a regulated open access management. In the former case although the community has some monopoly power over the use of the fishery resource within the management area, there are usually several fishing communities and a community cannot significantly influence the market price of the harvest. Moreover, it is also inevitable that if the resource is managed as a regulated open access resource, no single community could influence the price per unit of harvest. Consequently, we assume that the price per kilogram of harvest is fixed at q so that the gross revenue that the fisher obtains from fishing is qh.

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[2]Note that since the growth rate of the fish depends on the stock and index for mesh size, it is possible to solve for the stock as a function of mesh size and time from the growth function (i.e.$x = x(\alpha, t)$)

[3]Λ_z and Λ_{zz} are the first and second order partial derivatives of $\Lambda(\bullet)$ with respect to z.

[4]It is assumed for simplicity that there is no net migration of stock across management areas.

- *The cost of harvest*

Let the unit cost of harvest for each fisher be:

$$c(x, \alpha) = \frac{\varsigma}{a(\alpha)x} \tag{3}$$

where ς is a constant per unit cost of effort and $c(x,\alpha)h = c(E) = \varsigma E$ from equations (2) and (3). Thus, the illegal fishing net has the advantage of reducing the unit cost of harvest but not the cost per unit effort.

- *The expected cost of illegal fishing*

It is assumed that if the fisher is caught using the illegal net, he pays a fine F. Following the dynamic deterrence models of Davis (1988), Nash (1991) and Leung (1991, 1994), we assume that the violator i does not know the exact time of detection but only some probability distribution of the time of detection denoted $g_i(t) \equiv \frac{dG_i(t)}{dt}$ which is the continuous time analogue of the probability in a one-period expected utility model of Becker (1968). Where $G_i(t)$ is the cumulative density function (cdf) that defines the probability that detection would have occurred at time t in the future. The survivor function is therefore $(1 - G_i)$. Furthermore, without loss of generality, we assume that the violator will not be allowed to fish anymore if caught and will have zero exogenous income for the rest of the planning horizon. It is the case that illegal nets are seized when detected and we assume that the user will lose his fishing license or will be barred from fishing. This harsh punishment reduces the propensity to recidivate (Smith & Gartin, 1989). Thus, if the fisher is caught, he pays an expected present value of a fine of $\int_{t_0}^{T} Fg_i(t)e^{-\delta_i t}dt$ and gets nothing for the rest of the planning horizon. Note that the future benefits and costs are discounted at a discount rate of δ_i and since fishing nets are usually bequeathed to subsequent generations and mended continuously, we assume that the fisher has a planning horizon $T \to \infty$.

Let the probability that the offense will be detected within a very small interval of time t given that it had not been detected in the past (i.e. the hazard rate or the instantaneous conditional probability) be $p_i(\alpha, \tau) = \frac{g_i}{(1-G_i)}$ where τ is some exogenous enforcement effort of the management authorities, $p_{i\alpha} > 0$ and $p_{i\alpha\alpha} \geq 0^5$. The assumption that the hazard rate which is formed subjectively depends on the illegal mesh size stems from the fact that the size composition of catch of a fisher could signal his use of illegal mesh size. Using $g_i = p_i(\alpha, \tau)(1 - G_i)$ the expected present value of the fine can be rewritten as $\int_{t_0}^{\infty} Fp_i(\alpha, \tau)(1 - G_i)e^{-\delta_i t}dt$.

Moreover, we assume that mending the net to adjust the mesh size is costly. The cost of mending $k_i(\alpha)$ is increasing in the intensity of violation of the mesh size regulation (i.e., $k_{i\alpha} > 0$). Note that by implication the fisher does not incur this cost if he does not use illegal mesh size.

- *Anti-crime policy instruments and property right regimes*

Policy makers use two policy instruments to regulate illegal fishing. The instruments involve increasing the risk of punishment and/or the severity of punishment. Increasing the risk of punishment also implies increasing the *conditional* probability of detection (i.e. $p_i(\alpha, \tau)$) by increasing enforcement effort (i.e. τ). With regards to mesh size regulation, the fishery authorities either inspect nets at shore and at sea or inspect minimum landing size of the main species together with the existing mesh. Also the policy maker can increase the severity of punishment by increasing the fine or penalty. It is argued that while increasing the penalty is generally costless, increasing enforcement effort is unambiguously costly. As noted by Kuperan and Sutinen (1998), public expenditures

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[5]The specification of the (expected) probability as a function of violation level in a fishery and enforcement effort is consistent with Hatcher (2005).

on enforcement commonly constitute the largest cost element in regulatory programmes. In many developing countries, enforcement efforts are very low due to the high costs of monitoring and surveillance. The high cost is unaffordable to governments making the use of penalty a more attractive policy instrument (Akpalu, 2008). Moreover, since different property right regimes in fisheries lead to different levels of capitalisation and exploitation of fish stocks, the optimum fine is expected to differ across the different regimes.

2.1 Territorial use right in a fishery and illegal mesh size

Consider a situation where each community has the use right over a fishery management area. In a typical fishing community in a developing country, fishing activities are organised around a chief fisherman or the head of a beach management unit. A recent survey conducted in Ghana on violation of light attraction regulation showed that nearly all fishers within a fishing community violate the regulation if the chief fisherman does not comply with the regulation[6]. This section therefore models the decision problem of the head of the community or the beach management unit (i.e. the community social planner). Following the statement by Sandal and Steinshamn (2004), that a commercial fisher may often operate within a short-term horizon when he makes his decision, let the community social planner who is a representative agent commit to violating the mesh size regulation at time t_0.[7] Let $p_i(.)$ be the hazard rate of the social planner, h_i represent total harvest of the community i and assume that net migration of the stock across the community management areas is zero. It is assumed that if the illegal activity is detected, the community is carefully monitored to ensure complete compliance in the future or could be barred completely from fishing. Since we are interested in the impact of the illegal net on the levels of optimal stock and harvest, the analysis is limited to the segment of the value function that deals with the illegal activity. Thus, none of these two considerations will affect the outcome of our analysis and is ignored[8]. Beginning from the time of the commitment the objective of the planner will be to solve the following programme:

$$\max_{\{\alpha,h\}} \int_{t_0}^{\infty} \{((q - c(x,\alpha)) h_i - p_i(\alpha,\tau)F - k_i(\alpha)) (1 - G_i)\}e^{-\delta_i t}dt \tag{4}$$

subject to

$$\dot{G}_i = p_i(\alpha,\tau)(1 - G_i), \tag{5}$$

$$\dot{x}_i = \Lambda(x,\alpha) - h_i, \tag{6}$$

with $x \geq 0$, $x(0) = x_0$ and $\alpha(0) = \alpha_0$.

The constraints to equation (4) are the hazard rate (i.e. equation 5) which is an equation of motion; and the fish stock evolution equation (i.e. equation 6). As noted earlier, the values of α_i are inversely related to the mesh size[9]. These dynamics continue until the representative violator is

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[6] The light attraction is the technique that involves the use of artificial light in the night when the moon is out to attract and aggregate fish so that with any given level of effort, more fish can be harvested. It is illegal to use any light attraction equipment for fishing in Ghana. The project on violation of light attraction regulation in inshore fishery in Ghana is funded by CEEPA and is being undertaken by the author of this manuscript.

[7] Also due to the divergence between the short and long term impacts of a change in mesh size on catch, fishing communities may simply not be convinced about the need for a mesh size regulation and may consequently violate it.

[8] If the community is in complete compliance of the regulation after detection, the objective function will have an additional segment of

$$\int_{t_0}^{\infty} ((q - c(x)) h_i) G_i e^{-\delta_i t}dt.$$

[9] In the coastal countries of West Africa, for example, there is evidence of illegal use of decreasing mesh size over the years from the minimum legal size of 25mm to about 5mm (Yeboah, 2002). Consequently, it is reasonable to assume that α is a flow variable. Moreover, we suppose that the fisheries authorities have full information on the bio-dynamics of the fish stock. Hence, the minimum legal mesh size will lead to a sustainable management of the fish stock.

caught. Hence, the right hand side of the value function is multiplied by the survivor function.

The current value Hamiltonian associated with equations (4) through (6) for each fisher is equation (7). Following Johnston and Sutinen (1996), the shadow value of the fish stock, $\mu_i(t)$, is multiplied by the survivor function (i.e. $\mu_i(t)(1-G_i)$) since the fisher does not benefit from the stock after the illegal activity is detected. Note that $\lambda_i(t)$ is the shadow cost of the cumulative density function defining the time of detection or simply the shadow cost of taking the risk.

$$H = \left((q - c(x, \alpha)) h_i - p_i(\alpha, \tau) F - k_i(\alpha) + \lambda_i p_i(\alpha, \tau) + \mu_i \left(\Lambda(x, \alpha) - h \right) \right) (1 - G_i) \tag{7}$$

The maximum principle for the two control variables h_i and α_i are equations (8) and (9) respectively:

$$
\begin{aligned}
h &= h_{\max} \, if \, q - c(x, \alpha) > \mu_i (and \, x > x^{**}) \\
h &= 0 \, if \, q - c(x, \alpha) < \mu_i (and \, x < x^{**}).
\end{aligned}
\tag{8}
$$

$$\frac{\partial H}{\partial \alpha} = 0 \quad : \quad h_{i\alpha} (q - \mu_i) = p_{i\alpha} (F - \lambda_i) - \mu_i \Lambda_{i\alpha} + k_{i\alpha} \tag{9}$$

where x_{**} is the equilibrium stock under community territorial use right regime. Equation (8) defines inter-temporal profit maximising level of harvest. Thus, profit is maximised if the community chooses a level of harvest that equates its marginal profit (i.e. $q - c(x, \alpha)$) to the adjusted shadow value of the stock (i.e. μ_i). However, since h_i is not an argument in the maximum principle (i.e. equation 8), a singular solution is not trivial. If $q - c(x, \alpha) > \mu_i$ the existing stock exceeds what is optimally desired hence harvest will be at its maximum (i.e. $h_i = h_{i\max}$). On the other hand, if $q - c(x, \alpha) < \mu_i$ the existing stock is lower than what is optimally desired so the fisher will not harvest any fish at all (i.e. $h_i = 0$) until the stock recovers. For the purpose of our analysis, we assume that an interior solution exists (i.e. $x = x^*$, $q - c(x, \alpha) = \mu_i$ and $h_i^* = (0, h_{i\max})$) for tractability but without loss of generality.

Equation (9) defines inter-temporal profit maximising illegal mesh size. Thus, the fisher will choose the mesh size that equates expected net marginal benefit from violation (i.e. $h_{i\alpha} (q - \mu_i)$) to the marginal cost (i.e. $p_{i\alpha} (F - \lambda_i) + k_{i\alpha} - \mu_i \Lambda_{i\alpha}$) which is the difference between an adjusted fine and the shadow value of the growth of the stock. Note that since $c(x, \alpha)h = \varsigma E, \partial(c(x,\alpha)h) / \partial \alpha = \partial(\varsigma E) / \partial \alpha = 0$. Equation (9) can be re-specified as:

$$F = \frac{h_{i\alpha} q + \mu_i (\Lambda_{i\alpha} - h_{i\alpha}) - k_{i\alpha}}{p_{i\alpha}} + \lambda_i \tag{10}$$

Following Leung (1991) and Hatcher (2005), it is assumed that the society derives benefits from the (illegal) harvest that is equivalent to the direct net revenue from harvest $(q - c(x, \alpha)) h_i - k_i(\alpha)$ since the illegal catches are consumed. On the other hand, the society incurs a social cost of violation that depends on the intensity of violation (i.e. $m_i(\alpha)$). This social cost could be viewed as rent lost due to the use of smaller than optimal mesh size. Consistent with the complete territorial use right fishery, the social planner will optimise the net social benefit from violation subject to the dynamic equation of the stock (i.e. equation 1)[10]. From the maximum principle, the marginal social damage is $m_{i\alpha} = h_{i\alpha} q + \mu_i (\Lambda_{i\alpha} - h_{i\alpha}) - k_{i\alpha}$ which is the numerator of the first term of equation (10). Consequently, the fine necessary to internalise the technological externality should be set at:

$$F^*(\alpha_i, \lambda_i) = \frac{m_{i\alpha}}{p_{i\alpha}} + \lambda_i \tag{10a}$$

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[10]The Hamiltonian for the problem is

$$
\begin{aligned}
H &= (q - c(x, \alpha)) h_i - k_i(\alpha) - m_i(\alpha) + \mu_i \\
&\quad (\Lambda(x, \alpha) - h_i)
\end{aligned}
$$

.

Clearly, the fine is increasing in marginal social damage and the shadow value of the cumulative probability of detection but decreasing in the marginal hazard rate.

Proposition 1 *If a community that has use right over a fishery fishes using a net with illegal mesh size, the equilibrium stock level will depend on the size of the mesh and an effective discount rate (i.e. pure rate of time preference plus probability of detection). Consequently, if the illegal mesh size is used, the equilibrium stock and harvest are much lower than if it is not used.*

The proof of the preceding proposition is presented in the appendix. The basic idea here is to derive and compare the optimum stock and harvest levels for a situation where the community violates the regulation and the situation where it does not. In steady state $\dot{x} = 0$ and the expression for the optimal stock derived from the costate equation and the maximum principle is:

$$\left(\Lambda_x \left(x^{**}, \alpha^v\right) - \Lambda\left(x^{**}, \alpha^v\right) \frac{c_x(x^{**}, \alpha^v)}{(q - c(x^{**}, \alpha^{vv}))}\right) = \delta + p(\alpha^v, \tau), \tag{11}$$

where x^{**} is the equilibrium level of the stock if the fisher violates the regulation, α^v is an index for the inverse of illegal mesh size and $\delta + p(\alpha^v, \tau)$ is the *effective discount rate*. The corresponding equilibrium harvest is $h^{**} = \Lambda(x^{**}, \alpha^v)$. It could be inferred from equation (11) that $x^{**} = x(\tau, \alpha^v)$ and also verified that $\frac{\partial x^{**}}{\partial \tau} > 0$ and $\frac{\partial x^{**}}{\partial \alpha^v} < 0$. Consequently, an increase in enforcement effort, all other things being equal, will increase the optimum stock while increased intensity of violation will decrease the optimal stock. Moreover, a decrease in the illegal mesh size will result in a decrease in the growth rate of the fish stock and the cost of harvest but an increase in the effective discount rate. The overall effect of this is a sharp decrease in the optimal level of stock.

Conversely, if the community does not violate the regulation, the corresponding steady state interior solutions for the stock (i.e. equation 12) is computed from the solution from maximising equation 4 subject to equation 6.

$$\left(\Lambda_x \left(x^*, \alpha^L\right) - \Lambda\left(x^*, \alpha^L\right) \frac{c_x(x^*, \alpha^L)}{(q - c(x^*, \alpha^L))}\right) = \delta. \tag{12}$$

Comparing equations (11) and (12), it could be shown that if the community does not use the illegal net, the optimum level of the stock will coincide with that of fishery management authority and will be higher (see appendix for the proof). The implication as noted earlier is that increased exploitation of the resource leads to a high reduction in the equilibrium stock.

2.2 Regulated Open Access Fishery and illegal mesh size

Due to the high rate and uneven migration of many fish stocks, many fisheries are managed as open access resources, particularly in developing countries. Suppose a fishery is organised as a *regulated open access* where there is restriction on the mesh size but with no restriction on catch quantities. As noted in the fishery literature, open access fisheries dissipate potential profits due to free entry and exit of vessels in the industry (Gordon, 1954; Lueck, 1998). The competition for the stock by very large users leaves the resource with no shadow value and the industry commits a level of capacity that equates profits to zero. According to Edwards *et al.* (2004), a fish stock does not have any capitalised value in an open access or regulated open access resource since it is prohibitively expensive for individuals to exclude others and conserve the asset for future use. From the zero profit condition, an expression for the optimal stock could be derived. Suppose there are N fishing communities and each community represents a fishing unit with $h(.)$ being the harvest of the unit. Let the zero profit condition of the unit be $V_{00} = qa(\alpha^L)x_{oo}E_{oo} - \varsigma.E_{oo} = 0$, where $c(.)h(.) = \varsigma.E_{oo}$ and E_{oo} is open access level of effort (for all the communities). Consequently, the open access stock level is $x_{oo} = \varsigma/\alpha\left(\alpha^L\right)q$ if legal mesh size is used. Using this as a benchmark, we analyse two common cases of interest. The first is where the fishers in a community commit to fishing illegally

and adjust their mesh size to fish continuously until the illegal activity is detected while all other communities obey the regulation. Here also we assume that the community leader is the local social planner and what he does is copied by other members of his community. The second is where the community occasionally fishes with the illegal net until the illegal activity is detected while all other communities do not violate the regulation. Suppose that if the illegal activity is detected, the fisher pays a fine F_o and his fishing activity is closely monitored to ensure that he does not violate the regulation any more or is barred from fishing. The occasional fisher who violates the fishing regulation will maximise the value function given by equation (13) with respect to the intensity of violation[11]. The corresponding first order condition of the problem is equation (14).

$$\underset{\{\alpha_i^v\}}{Max} V_i = (qh_i - c(x, \alpha_i^v)h_i - p(\alpha_i^v, \tau)F_o - k(\alpha_i^v))(1 - G). \tag{13}$$

$$\frac{\partial V_i}{\partial \alpha_i^v} = 0: \quad F_o = \frac{qh_{\alpha_i^v} - k_{\alpha_i^v}}{p_{\alpha_i^v}}. \tag{14}$$

Note that if $p_{\alpha^v}F_o$ is replaced by $m_{o\alpha_i}$ in the social planner's problem, we have $F_o^*(\alpha_i^v) = \frac{m_{o\alpha_i^v}}{p_{\alpha_i^v}}$ under the regulated open access regime.

Let H denote total harvest in the fishery (by all units or communities) so that $H = h_{i0} + H_{-i0}$ where h_0 is open access levels of harvest for unit i and H_{-i0} is the total harvest for all other $N - 1$ communities that do not violate the regulation. If symmetry is assumed in open access equilibrium, the profit dissipation condition (i.e. equation 15) also holds. Thus,

$$q(h_{i0} + H_{-i0}) - c(x_0, \alpha_i^v)(h_{i0} + H_{-i0}) - p_i(\alpha_i^v)F_o - k(\alpha_i^v) = 0, \tag{15}$$

or

$$q(a(\alpha^v) + (N-1)a(\alpha^L))e_{io}x_o - Nce_{io} - p_i(\alpha_i^v)F_o - k(\alpha_i^v) = 0$$

where x_o is open access level of stock, $c(.)h(.) = N_\varsigma.e_{i0}$ and $E_o \equiv Ne_{io}$ is an open access level of effort. For simplicity but without compromising generality, we assume that the adjustment cost of the illegal net is zero (i.e. $k(\alpha_i^v) = 0$). Combining equations (14) and (15) and substituting qh_{α_i} for the expected fine (i.e. $p_{\alpha_i}F_o$) while assuming symmetric fishing effort gives[12]

$$x_o = N_\varsigma \left/ \left(q\left(\alpha\left(a^v\right) + (N-1)\alpha\left(\alpha^L\right)\right) - \frac{\varepsilon_\alpha}{\eta_\alpha}\alpha\left(\alpha^v\right)\right) \right. \tag{16}$$

where $\eta_\alpha = \frac{\alpha_i p_\alpha}{p(\alpha_i)}$ is the elasticity of hazard rate and $\varepsilon_\alpha = \frac{\alpha_i a_\alpha}{a(\alpha_i)}$ is the elasticity of catchability coefficient. It follows from the above equation that the necessary condition for the existence of positive equilibrium stock is that the denominator must be positive. Moreover, an increase in the hazard elasticity relative to the elasticity of the catchability coefficient will lead to a reduction in the optimal stock. Note that an increase in the hazard elasticity implies an increase in the effective discount rate.

Proposition 2 *If an illegal mesh size is used in a regulated open access fishery, the equilibrium level of stock will be lower than otherwise if the elasticity of the catchability coefficient is less than the elasticity of the hazard rate.*

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[11] Since the fishery is characterised by free entry and exit, if the probability of getting away with the crime at any point in time is $1 - b_i$, following the standard model of Becker, the expected utility function is $E(u_i) = (qh_i - c(x, \alpha_i)h_i - k(\alpha_i))(1 - b_i) + (qh_i - c(x, \alpha_i)h_i - k(\alpha_i) - F_o)b_i = qh_i - c(x, \alpha_i)h_i - k(\alpha_i) - b_iF_o$. Moreover, since the fisher will not be allowed to fish anymore after the act is detected, expected utility is multiplied by the survivor function and the result is the value function (i.e. equation 13).

[12] If it is assumed that n out of N communities violate the regulation, then the optimum stock will be $x_o = N_\varsigma \left/ \left(q\left(na(\alpha^v) + (N-n)a(\alpha^L)\right) - \frac{\varepsilon_\alpha}{\eta_\alpha}na(\alpha^v)\right) \right.$.

This implies that if fishing is done with the illegal mesh size, the regulated open access stock will be higher than that which prevails in the absence of fishing illegally if $x_0 < x_{00} = \frac{\varsigma}{a(\alpha_i^L)q}$. As has been shown in the appendix, if $k(\alpha_i^v) = 0$ is assumed for simplicity we have $\varepsilon_\alpha < \eta_\alpha$. Consequently, if a community violates the regulation, the optimum level of stock will be lower compared to the situation where it does not violate the regulation if changing the illegal mesh size leads to a higher than proportionate change in the risk of punishment relative to the proportionate change in the benefit from harvest.

Now, suppose that a fishing community violates the regulation continuously until the illegal activity is detected. The planner for the unit will maximise equation (13) with respect to the intensity of violation subject to the hazard rate (i.e. equation 5). The corresponding Hamiltonian and the maximum principle are equations (15a) and (16a) respectively.

$$H_{oi} = (qh_i - c(x, \alpha_i)h_i - p(\alpha_i, \tau)F_o - k(\alpha_i) + \lambda_i p(\alpha_i, \tau))(1 - G_i) \tag{13a}$$

$$\frac{\partial H_{io}}{\partial \alpha_i} = 0: \quad p_{\alpha_i} F_o^{**} = qh_{\alpha_i} - k_{\alpha_i} + \lambda_i p_{\alpha_i}$$

$$F_o^{**}(\alpha_i, \lambda_i) = \frac{qh_{\alpha_i} - k_{\alpha_i}}{p_{\alpha_i}} + \lambda_i \tag{14a}$$

Also the following profit dissipation condition holds:

$$q(h_{i0} + H_{-i0}) - c(x_0, \alpha_i^v)(h_{i0} + H_{-i0}) - p_i(\alpha_i^v, \tau)(F_o - \lambda_i) - k(\alpha_i^v) = 0 \tag{15a}$$

If it is assumed that the adjustment cost of the illegal net is zero (i.e. $k(\alpha_i^v) = 0$ and equations (14) and (15) are combined, equation (16a) will be obtained if $qh_{\alpha_i} + p_\alpha \lambda_i$ is substituted for the expected fine (i.e. $p_{\alpha_i} F_o$).

$$x_o' = N\varsigma \left/ \left(q\left(\alpha(a^v) + (N-1)\alpha(\alpha^L)\right) - \frac{\varepsilon_\alpha}{\eta_\alpha}\alpha(\alpha^v)\right)\right. \tag{16a}$$

Note that equations (16) and (16a) are the same which implies, that all other things being equal, the optimal level of stock that will prevail if the community violates the regulation occasionally will be the same as what will prevail if it violates the regulation continuously given that the expected marginal fine equates the expected marginal gain from violation. Also, comparing the fines under the regulated open access, it is clear that due to the positive cost of taking the risk of doing illegal fishing continuously, the potential violator is more likely to be caught sooner than later and should therefore be penalised less relative to the situation where the community violates the regulation occasionally.

Proposition 3 *The fine for using a net with illegal mesh size in a regulated open access fishery where a community fishes continuously must be higher than the fine in a fishery where the community has complete use right over the fishery but fishes illegally.*

The proof presented in the appendix shows that $F_o^{**} > F^*$. The intuition here is that while the community with complete use right over the fishery resource may be myopic from the societal point of view and fish with a net with illegal mesh size, it internalises the impact of harvesting activities on the dynamics of the stock. Consequently, the steady state level of the fish stock would be higher and a relatively lower penalty is needed to correct the damage. Conversely, since the competition for the stock in an open access resource may lead to overcapitalistion and overexploitation, with the resource having no shadow value, fishing using the net with illegal mesh size exacerbates the resource use externality and a relatively high penalty is needed to mitigate the externality.

9

3 Conclusion

This paper extends the one-period or static expected utility model to a dynamic one to accommodate a chronic fishery crime problem in many (developing) countries. It incorporates time and punishment to analyse the effect of using fishing nets with illegal mesh size on fish stocks and harvest under the two regimes. The first regime is where each community claims a territorial use right over the resource in a management area and the second regime is regulated open access where each community can harvest any quantity of the resource within the entire management area as long as the mesh size regulation is obeyed. The optimum fine necessary to discourage the illegal activity is derived and compared under the two regimes.

It has been shown that if the community has territorial use right but fishes using a net with illegal mesh size, the optimal stock and harvest will be much lower than what will prevail if there is no illegal fishing. This is because in addition to the illegal mesh size decreasing the cost of harvest and intrinsic growth rate of the stock, it increases the effective discount rate. Note that a higher discount rate leads to increased harvest and stock levels. The effective discount rate is the sum of benefit discount rate and the conditional probability of detection. However, if the fishery is managed as a regulated open access resource, the optimum stock level will be lower if the net with illegal mesh size is used and the elasticity of catchability coefficient of the mesh size is lower than the elasticity of the hazard rate.

An important policy recommendation from the analysis is that the fine should be higher for fishing under open access compared to the situation where a community has the territorial use right over a management area.

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4 Appendix

Proof of Proposition 1. ∎

The proof of the preceding proposition requires deriving and comparing the harvest levels under the two situations. Let α^v and α^L denote indexes for the inverse of illegal and legal mesh sizes respectively. The costate equation associated with the fish stock from the Hamiltonian (i.e. equation 7) is $\dot{\mu} - (\delta + p(\alpha^v, \tau))\,\mu = -\frac{\partial H}{\partial x}\frac{1}{1-G}$, noting that from the Hamiltonian $\frac{d}{dt}(\mu(1-G)) = \dot{\mu}(1-G) - \mu g$. In steady state $\dot{x} = 0$ and $\dot{\mu} = 0$. The expression for the optimal stock which is derived from the costate equation and equations 7 and 9 is equation 11.

$$\left(\Lambda_x\left(x^{**}, \alpha^v\right) - \Lambda\left(x^{**}, \alpha^v\right)\frac{c_x(x^{**}, \alpha^v)}{(q - c(x^{**}, \alpha^v))}\right) = \delta + p(\alpha^v, \tau), \tag{A1}$$

where x^{**} is the equilibrium level of the stock if the fisher violates the regulation. The corresponding equilibrium harvest is $h^{**} = \Lambda(x^{**}, \alpha^v)$. If the fisher does not violate the regulation, the corresponding steady state interior solutions for the stock is computed from the solution from maximisation of equation 4 subject to equation 6. Thus,

$$\delta = \left(\Lambda_x\left(x^*, \alpha^L\right) - \Lambda\left(x^*, \alpha^L\right)\frac{c_x(x^*, \alpha^L)}{(q - c(x^*, \alpha^L))}\right) \tag{A2}$$

The corresponding steady state harvest is $h^* = \Lambda(x^*, \alpha^L)$. From equation (11), we know that $c_x < 0$. Furthermore, the last term in the bracket of equation (11) is less than that of equation (12) (i.e. $\frac{c_x(x^{**}, \alpha^v)}{q - c(x^{**}, \alpha^v)} < \frac{c_x(x^*, \alpha^L)}{q - c(x^*, \alpha^L)}$). This is because $\frac{c_x(x^{**}, \alpha^v)}{c(x^{**}, \alpha^v)} = \frac{c_x(x^*, \alpha^L)}{c(x^*, \alpha^L)}$ and $q - c(x^{**}, \alpha^v) > 0$. Also without violation the growth of the stock is higher than what prevails in the presence of violation for any biomass level and $\Lambda_x\left(x^*, \alpha^L\right) > \Lambda_x\left(x^{**}, \alpha^v\right)$, hence $x^{**} << x^*$

Proof of Proposition 2. ∎

Suppose for simplicity that $k(\alpha_i^v) = 0$. The zero profit condition (i.e. equation 15) can be restated as:

$$q(a(\alpha^v) + (N-1)a(\alpha^L))e_{io}x_o - N_\varsigma e_{io} - p_i(\alpha_i^v)F_o = 0 \tag{A3}$$

By substituting qh_{α_i} for the expected fine (i.e. $p_{\alpha_i}F_o$), the equilibrium stock is:

$$x'_o = N\varsigma \Big/ \left(q\left(\alpha\left(a^v\right) + (N-1)\,\alpha\left(\alpha^L\right)\right) - \frac{\varepsilon_\alpha}{\eta_\alpha}\alpha\left(\alpha^v\right)\right) \tag{A4}$$

where $\eta_\alpha = \frac{\alpha_i p_\alpha}{p(\alpha_i)}$ is the elasticity of hazard rate and $\varepsilon_\alpha = \frac{\alpha_i a_\alpha}{a(\alpha_i)}$ is the elasticity of catchability coefficient. From equation (A4), it follows that the necessary condition for existence of equilibrium stock is $\varepsilon_\alpha < \eta_\alpha\left(1 + (N-1)a(\alpha^L)/\alpha\left(\alpha^v\right)\right)q$. If fishing is done with the illegal mesh size x_0 (from equation 16) is less than the stock under the complete compliance regulated open access (i.e. $x_{oo} = \frac{\varsigma}{a(\alpha_i^L)q}$) if:

$$x_o < x_{oo} \Rightarrow N\varsigma \Big/ \left(q\left(\alpha\left(a^v\right) + (N-1)\,\alpha\left(\alpha^L\right)\right) - \frac{\varepsilon_\alpha}{\eta_\alpha}\alpha\left(\alpha^v\right)\right) < \frac{\varsigma}{a(\alpha_i^L)q} \tag{A5}$$

.Using harvest as the numeraire (i.e. $q = 1$) some rearrangements of the terms in equation (A5) gives:

$$\varepsilon_\alpha < \eta_\alpha\left(1 - \frac{a(\alpha_i^L)}{a(\alpha_i^v)}\right) \tag{A6}$$

Since $\frac{a(\alpha_i^L)}{a(\alpha_i^v)} \in (0,1)$ it follows that $\varepsilon_\alpha < \eta_\alpha$

Proof of Proposition 3. ∎

From equations (10a) and (14a) we have $F^*(\alpha,\lambda) = \frac{m_{i\alpha}}{p_\alpha} + \lambda_i$ where $m_{i\alpha} = h_{i\alpha}q + \mu_i\left(\Lambda_{i\alpha} - h_{i\alpha}\right) - k_{i\alpha}$, and $F_o^{**}(\alpha,\lambda) = \frac{m_{o\alpha}}{p_\alpha} + \lambda_i$ where $m_{o\alpha} = h_{i\alpha}q - k_{i\alpha}$. By comparing the two equations, it can be seen that $F^* < F_o^{**}$ if $\mu_i\left(\Lambda_{\alpha_i} - h_{i\alpha}\right) < 0$. But we know that $\Lambda_{\alpha_i} < 0$ and $h_{i\alpha} > 0$ hence $F^* < F_o^{**}$