Determinants of frequency of violating fishery regulation in dynamic deterrence models

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Abstract

Due to market-related and institutional circumstances, frequency of non-compliance with regulation is considered more suitable than intensity measures of violation in the artisanal fisheries of developing countries. This paper accordingly extends the two times dynamic deterrence model (DDM) to use frequency instead of intensity of non-compliance as a measure of violation rate. The method of comparative statics is employed to derive analytical results on the sensitivity of optimal violation to a number of key factors of high relevance to compliance with regulation designed to protect against over-fishing. Analytical results obtained with this extended DDM confirm findings of earlier empirical studies employing alternative static and dynamic formulations and reveal a more interesting economic meaning of modelled relations. The study concludes that in developing country artisanal fisheries, where probability of detection, enforcement and levels of fine are typically low and poverty levels leading to high impatience about the future (discount rate), violation rates are bound to be high. The relative magnitude of the effects of each of these factors on compliance with regulation, however, remains an important empirical question that requires further investigation for prioritisation of policy actions.

Keywords: fishery regulation, dynamic deterrence model, frequency of violation

1. **Introduction**

Long-run benefits from the fishing industry have been negatively affected worldwide by the practice of illegal fishing. This has become a global problem, presenting serious threats to fish stock rebuilding (Millennium Ecosystem Assessment 2005 and Sumaila, Alder & Keith, 2006). The problem of illegal fishing is usually attributed to failures in fishery regulation due to weak enforcement and monitoring of compliance with laws and regulations, and tolerance towards corruption and cheating (Charles, Mazany and Cross, 1999 and MEA, 2005).

According to Pauly (1996), half of the world's fish catches are from the tropical waters of developing countries. However, due to the poor management and open access conditions, these fisheries have been over-exploited, leading to significant declines in fish resource stocks (Andrew, Hall and Ratner, 2007). Over-fishing and illegal fishing (particularly the practice of fishing with small mesh sizes) is very common in developing countries. It is driven by the selfish motive of maximising private profits from open access fishing waters and the difficulties of implementing regulations. For example, Akpalu (2008 and 2009) and Eggert and Lokina (2009) found that the use of small mesh sizes seriously affected the fishery resources in Ghana and Tanzania, respectively. In India, where the prescribed minimum size is 35 mm, stake nets with mesh sizes less than 5 mm have been used to catch juvenile fish (Srinivasa, 2005). Fishers in Sudan use mesh of 2 cm instead of the prescribed 4 cm size to catch species used for food processing (Hamid, 2000), putting serious pressure on the country's fish resources.

Many theoretical and empirical studies have been conducted to determine the reasons for non-compliance with fishery regulation. Violation of fishery regulation is considered a crime committed in pursuit of maximising profits from fishing in closed areas, catching with non-prescribed mesh size or fishing in a prohibited zone or any behaviour against the law (Akpalu, 2008; Charles, Mazany and Cross, 1999; Eggert and Lokina, 2009; Furlong 1991; Hatcher *et al.,* 2000; and Sumaila, Alder & Keith, 2006). All studies agree that the main reason for violation is the high profits fishers gain from fishing illegally, which act as a strong incentive for non-compliance. Sumaila, Alder and Keith (2006) estimate gains from illegal fishing to amount to about 24 times the fine paid as a punishment, compared to the 5 times the penalty estimated by King and Sutinen (2010).

The behaviour of violation of laws was first studied by Becker (1968). Many studies have used Becker's model of the economics of crime and punishment under both static and dynamic formulations. Static deterrence models assume that violators face a one time period decision problem of maximising expected utility from illegal fishing, i.e. choice of either to follow or not follow fishery regulations (Charles, Mazany, and Cross, 1999; Furlong, 1991; Hatcher and Gordon, 2005; Kuperan and Sutinen, 1998; Sutinen and Kuperan 1999 and Sumaila, Alder & Keith, 2006). On the other hand, in dynamic formulations, the fisher will be optimising his/her accumulative gains over time until he/she gets caught because the crime is committed repeatedly (Akpalu, 2008 and Leung, 1991). In addition, the Dynamic Deterrence Model (DDM) also considers the chance of the danger of getting caught over time and differences in fishers' time preference towards the future (discount rates) (Akpalu, 2008, Davis 1988 and Lueng, 1991).

In these models, the violation rate in fishery regulation is usually measured by "intensity of violation" or "frequency of violation". Violation rates have so far been mainly specified only as "intensity" in dynamic deterrence analysis (Akpalu, 2008) whereas "frequency of violation" has been used only in static deterrence models (Eggert and Lokina, 2009; Furlong, 1991 and Sutenin and Kuperan, 1999). No study has yet used frequency as a measure of violation rates in a dynamic formulation in spite of the proven advantages of using frequency over intensity measures in static deterrence models.

This is an important gap in the existing theoretical and empirical literature in DDM since considering frequency as a measure has many advantages. First, intensity of violation, which is measured by the proportion of illegal catch sold in the market, may fit developed countries but is highly unlikely to be applicable in developing countries, where property rights are more ill-defined and it is relatively easier for fishers to escape been caught. This makes it very hard to estimate the total catch per day that includes violating harvests and hence presents a data problem. Second, by not employing frequency as a measure of violation rate one misses the opportunity of capturing the direct link between violation rates and opportune time periods for illegal fishing (seasonality). This is due to the fact that during the months of active breeding; the quantities of small fish are high, which encourages illegal fishing compared to months of no breeding. Thirdly, the use of frequency also helps to classify fishers into categories of violators, a typology that will help policy makers and managers design policy measures and instruments suited for each group. Finally, illegal catches are not sold on formal fishing markets and efforts are made to avoid being seen by monitors and are most of the time distributed to customers who process such catches for own use outside formal channels.

The aim of this paper is therefore to fill this gap by developing a DDM that uses frequency of violation as the measure of violation rates in analysing determinants of non-compliance with fishery regulation. Analytical results of the developed model will be compared with findings of static and dynamic models using intensity rather than frequency measures of violation.

The next section of the paper develops the theoretical framework that adapts the DDM to use frequency instead of intensity measures. Section three derives analytical results under dynamic formulations employing frequency measures of violation. Derived comparative static results are compared with earlier results obtained from both statics and DDMs using intensity measures. Section four concludes with key implications of the results.

2. Dynamic deterrence with frequency measures of violation rates

This study employed the two time periods DDM of Akpalu (2008), Davis (1988) and Leung (1991), which postulates that violators seek to maximise their expected discounted profit over two time periods. In the first period, offenders gain from illegal activities until the time they get caught and pay a fine. Violators will then engage only in legal activities thereafter, concluding the second period choice problem. The repeated nature of the crime and differences in fishers' time preference towards the future (discount rates) make them consider maximising the sum of stream of net benefits over time using all their skill and experience to prolong the time before getting caught.

In this section we used the above DDM framework to the case of frequency measures of violation. Frequency of violation measures how frequently fishers have violated regulation. Papers which have used frequency of violation have incorporated the measure in empirical deterrence models (Eggert and Lokina, 2009; Hatcher and Gordon, 2005; and Sutinen and Kuperan, 1999). For instance, Furlong (1991) and Sutenin and Kuperan (1999) assumed that a fisher has a fixed amount of time, part of which he spends in illegal fishing with no explicit classification of violator by type. Eggert and Lokina (2009), on the other hand, adopted a typology of violators but did not account for the dynamic nature of violation, i.e. alternate periods of violation and non-violation for the same fisher that continue repeatedly.

Three types of fishermen have been observed in developing countries (Eggert and Lokina, 2009; Kuperan and Sutenin, 1998). Non-violators who own only prescribed nets are typically well-off fishermen who most of the time have other sources of income for survival. For this group, using small size nets is time consuming and small fish caught with these nets command low prices. The second group is the chronic violators who own

only illegal nets because they cannot afford to buy both types of nets. For this relatively poor group, the small size fish, though not profitable, guarantee a subsistence catch for own use and survival. The third group is alternate violators, who own both types of nets and use the legal size during months of big size fish and the illegal size during months when big size fish are no longer available. This paper therefore adapted the DDM by using frequency of violation in terms of the number of months a fisher used a small mesh size. Accordingly, three groups of violators are defined as follows: Non-violators (NV) refers to those who never violate; occasional violators (OV) are those who tend to violate at least once but tend to try again for from 1 month up during the time period of violation and chronic violators (CV) who violate all the time. Eggert and Lokina (2009) and Kuperan and Sutenin (1998) noted that most fishers in developing countries are alternate violators.
Assume that *m* is the frequency of illegal fishing measured as the number of sub-periods of fishing per unit time considered (i.e. it could be number of months, days or years of illegal fishing). If in any period the fisher uses small (illegal) mesh sizes, he targets both mature and immature fish (i.e. m> 0) and his profit Πm from violation is:

$$\Pi m \ (m, c, p_a, Q_m, E_m, s) = p_a * m * Q_m (E_m, s) - cm \qquad (1)$$

Where p_a refers to the average composite price of fish (mature and immature)[1], *c* is total cost of fishing illegally including fixed (sunk) costs of the illegal nets and the variable efforts' cost per period m. Q_m is the quantity of fish caught using illegal nets (i.e. mix of mature and immature) per period of violation, which is a function of the effort used to catch this quantity per period E_m and the stocks of fish (mixed mature and immature).

Assume that the time of the entire planning horizon is T; then the time of fishing illegally extends from t=1… m, where m as defined as above (number of periods of illegal fishing till detection). We now assume that after being caught at the end of the first period, the fisher will cease using illegal nets and continue to maximise his profit[2] from only legal catches forever (i.e. from t=m+1 …∞, second period of DDM)[3] earning profit Πn :

$$\Pi n \ (n, b, p_n, Q_n, E_n, x) = p_n * n * Q_n (E_n, x) - bn \qquad (2)$$

Where *n* is the number of times of fishing legally, p_n is the price of normal (legal mature size) catch, *b* is total cost that include a fixed (sunk) cost of the legal net and the variable

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[1] Average price is used because of the fact that the catch from illegal nets include both mature and immature catches and fishers usually sell their catch of mixed sizes to middlemen in weight units (kg) at a reduced price depending on the percentage of small fish.

[2] Though DDM assumes fishers violate in order to maximize profits, in developing countries where rivers and lakes are over-fished, fishers violate for survival and to sustain life (Sterner, 2003).

[3] Though the planning horizon is infinite, in the second period n is used as number of times of legal fishing given the fact that non-violators can't live forever.

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efforts' cost, and Q_n is the quantity of normal catch only in periods of no violation specified as a function of the effort E_n and the stock of only mature fish x per time period.

This means that the total profit of the fisher over the two periods will be the sum of Πm and Πn :

$$\Pi m + \Pi n = P_{a*} m * Q_m - c*m + P_{n*} n * Q_n - b*n \qquad (3)$$

Following Davis (1988), we assume that the violator does not know the exact time of detection, but has knowledge of the probability distribution of the detection time. Assume a continuous distribution of time of detection t with the probability density function (pdf) given by $g(t)$ and the cumulative density function (cdf) given by $G(t)$ so that $g(t) = dG(t)/dt$. Then, the probability of being caught at time t is $G(t)$ and the probability of not being caught at time t is $\{1 - G(t)\}$.

We also assume that if the fisher is caught, he pays a fine *F*, which is a fixed fine plus the cost of the net, which will be seized immediately. Taking the probability of being fined given that the fisher is detected being R[4], the expected present value of the fine is (Davis, 1988):

$$R\int_0^\infty Fg(t)e^{-\delta t}dt \qquad (4)$$

We now assume that the fisherman is maximising his expected discounted profit V(.) over an infinite time horizon.

$$V(.) = \int_0^\infty e^{-\delta t}\begin{Bmatrix}(p_a.m.Q_m(E_m, s) - cm + p_n.n.Q_n(E_n, x) - bn)(1 - G(t) + \\ (p_n.n.Q_n(E_n, x) - bn)G(t) - RFg(t)\end{Bmatrix}dt \qquad (5)$$

Where V(.) is the value function, δ is the discount rate. Equation (5) states that the fisher's expected discounted net profit is equal to the expected discounted profit from illegal fishing (the first and second terms) plus the expected discounted profit from legal fishing (the third term) minus the expected fine from violation (last term).

Probability of detection is modelled as a hazard rate, which is the conditional probability of having a spell length of exactly t, conditional on survival up to time t (Jenkins, 2004). Following the literature, the probability of detection is equated to the hazard rate and set to be independent of time. Probability of detection is difficult to calculate and has been observed to be always low (Furlong, 1991; Sumaila, Alder & Keith, 2006; Sutinen and Kuperan, 1998). While Becker (1968) and some papers using static formulations argue for a high penalty to deter violation, many papers suggest that crime is more likely to be

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[4] The use of expected fines is due to considerations such as corruption, as some fishers may escape paying fines even if they are caught.

deterred by increasing the hazard of being caught than raising the fine (Akpalu, 2008; Davis, 1988; Furlong, 1991and Lueng, 1991).

Used in this context, the hazard rate is the probability that a law-breaking fisher will be caught just after time *t*, given that he escaped the police until time *t*. This probability is given by[5]:

$$\Pr(E,m) = \frac{g(t)}{1-G(t)} \tag{6}$$

Pr is the probability of detection of a violator given that he/she has not been detected before, *E* is the constant enforcement effort of the regulator[6], *m* as defined earlier is the rate of violation (number of months per year that the fisher fishes illegally) and (1-G (t)) is the survival function. *E* and *m* are time-invariant. Then, we assume that the hazard rate increases with *m* at an increasing rate (i.e. $\frac{\partial \Pr}{\partial m} > 0$), $\frac{\partial^2 \Pr}{\partial m^2} \succ 0$. This assumption of a concave relation between probability of detection and violation rate is very important, following the standard dynamic deterrent model of Davis, (1988). Furthermore, we assume that no fisher will be falsely detected, that is:

Pr (0) =0

$$\Pr(m) = \frac{g(t)}{1-G(t)} = \frac{-d(1-G(t)/dt}{1-G(t)} \tag{7}$$

$$\Pr(m) = \frac{-d\ln(1-G(t)/dt}{d(t)} \tag{8}$$

Integrating both sides, we reach:

$$\int_0^t \Pr(m)d\tau = -\ln\{1-G(t)\} \tag{9}$$

$$\ln\{1-G(t)\} = -\int_0^t \Pr(m)d\tau \,;\, \{1-G(t)\} = \exp(-\int_0^t \Pr(m)d\tau\,) \tag{10}$$

$$\{1-G(t)\} = e^{-\int_0^t \Pr(m)d\tau} \tag{11}$$

As is the case in most developing countries, fishing is managed as "regulated open access", meaning there are no limits to catch or efforts but that fishers must observe certain regulations such as fishing licenses (including boat licenses) and gear restrictions (see Akpalu, 2008). We assume however, that the rate of violation (m) is constant over time, then:

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[5] We assume that the hazard rate is independent of time, meaning that we are assuming an exponential distribution for the time of detection.

[6] Note that the enforcement is constant and independent of the individual. That is because if we use cross-section data, the perception of enforcement may differ among fishers. But this cannot influence directly the probability of detection, though an influence may occur indirectly through m. The fisher may decrease his rate of violation because of perception of high level of enforcement. We will not deal with that situation here. We will then ignore E in the rest of the paper.

$$\{1-G(t)\}=e^{-\Pr(m)t} \;;\; \{G(t)\}=1-e^{-\Pr(m)t} \;, and,\; g(t)=\Pr(m)e^{-\Pr(m)t} \tag{12}$$

By substituting the values of $g(t)$ and $G(t)$ in equation (5), assuming that all other variables are constant over time, integrating and rearranging terms, we get the value function of each violator, given by (annexure A):

$$V(.)=\frac{(p_a.m.Q_m(E_m,s)-cm)-(p_n.n.Q_n(E_n,x)-bn)-\mathrm{R\ F}\Pr(\mathrm{m})}{\Pr(\mathrm{m})+\delta}+\frac{(p_n.n.Q_n(E_n,x)-bn)}{\delta} \tag{13}$$

The first term is the pure discounted profit from illegal fishing, while the second term is the discounted profit from legal fishing. Since the study concentrates on the discounted illegal profit, which depends on the rate of violation (first term), the second term will be dropped, hence the objective of the fisher will be to maximise the discounted illegal profit given by:

$$V(.)=\frac{(p_a.m.Q_m(E_m,s)-cm)-(p_n.n.Q_n(E_n,x)-bn)-\mathrm{R\ F}\Pr(\mathrm{m})}{\Pr(\mathrm{m})+\delta} \tag{14}$$

Then, the optimal level of violation for each fisher is given by:

$$m^*=\arg\max\ \frac{m(p_a.Q_m(E_m,s)-c)-n(p_n.Q_n(E_n,x)-b)-\mathrm{R\ F}\Pr(\mathrm{m})}{\Pr(\mathrm{m})+\delta} \tag{15}$$

Assuming an interior solution, the first order condition is given by:

$$\frac{\partial V}{\partial m}=\frac{(p_a.Q_m(E_m,s)-c-RF\Pr_m)*(\delta+\Pr(m))-\Pr_m(m(p_a.Q_m(E_m,s)-c)-n(p_n.Q_n(E_n,x)-b)-\mathrm{RF}\Pr(\mathrm{m}))}{(\delta+\Pr)^2}=0 \tag{16}$$

Where $\Pr_m$ means the differential of Pr with respect to *m*. Condition (11) suggests that illegal fishing will be attractive up to the point when

$$p_a.Q_m(E_m,s)-c-RF\Pr_m=\frac{(\Pr_m(m(p_a.Q_m(E_m,s)-c)-n(p_n.Q_n(E_n,x)-b)-\mathrm{R\,F}\Pr(\mathrm{m})}{\delta+\Pr} \tag{17}$$

Which is the point where the optimal level of illegal fishing is reached and beyond which net expected marginal benefits (left hand side) will be less than the discounted net marginal cost (right hand side) of illegal fishing. Note that in expression (17) the fisher takes into account the cost advantage of illegal fishing (c-b) and the marginal expected fine R, F, and $\Pr_m$.

The fisher will never fish illegally (i.e. m=0) if:

$$p_a.Q_m(E_m,s)-c-RF\Pr_m<0 \tag{18}$$

This condition is fulfilled for those who never violate, i.e. the “non-violators”. This equation could only be positive if m becomes positive, i.e. if the fisher starts to violate and thereby earns more money. The question becomes: why then don't fishers want to violate? There are two justifications for this; first, it can be attributed to the influence of some other important, non-monetary reasons that prevent fishers from violating regulation (i.e. normative factors), such as morals and beliefs. Second, non-violators might be a well-off group that obtain one type of net (legal net) and fish during the season of big size fish simply because they are involved in another job during the other season. For them, fishing is a secondary source of money. However, in a poor institutional environment with an efficient illegal technology and loose enforcement, condition (18) is highly likely to be positive. For instance, in a community of chronic violators, we can deduce from equation (18) that violators will totally switch to illegal fishing if:

$$p_a.Q_m(E_m,s)-c-RF\mathrm{Pr}_m \geq \frac{(\mathrm{Pr}_m(m(p_a.Q_m(E_m,s)-c)-n(p_n.Q_n(E_n,x)-b)-\mathrm{R\,FPr(m}}{\delta+\mathrm{Pr}} \qquad (19)$$

This condition is fulfilled for those who are full-time violators, i.e. the "chronic violators". Chronic violators are the poorest fishers, who own only illegal nets because they cannot afford to buy both types of nets. For them, though not profitable, small size nets guarantee subsistence catches for survival, as their aim is to have some income for the whole year, no matter how small**.** Note that the condition in equation (18) is independent of the discount rate, but depends on the expected marginal fine.

3. The effect of factors on the optimal violation rate

This section employs the method of comparative statics to explore the direction of the effect of each factor on the rate of violation. We start from the first order equilibrium conditions to derive comparative statics results on the effects of various factors on the frequency of violation using the implicit differential rules in equilibrium (Chiang, 1984). These results will help us understand the nature of the effects of some factors of policy relevance on the optimum value of frequency of violation.

Let us denote first order conditions of equation (16) by K and use it to derive the comparative statics of the model with respect to its parameters (See detailed derivation of results in Annexure B).

(1) Effect of probability of fining R (enforcement)

$$\frac{\partial K}{\partial R} = \frac{-F\mathrm{Pr}_m\delta}{(\delta+\mathrm{Pr})^2} < 0 \qquad (20)$$

Equation (20) yields a negative value given the fact that Pr_m, F and δ are all positive. This result implies that violation rate/frequency (m*) decreases with an increase in the expected probability of paying the fine R.

(2) Effect of level of fine F

$$\frac{\partial K}{\partial F} = \frac{-R\mathrm{Pr}_m \delta}{(\delta + \mathrm{Pr})^2} < 0 \quad (21)$$

The same argument used in equation (20) applies to equation (21), suggesting that frequency of violation (m*) decreases with an increase in the amount of the fine (F).

(3) Effect of probability of detection Pr(m)

$$\frac{\partial K}{\partial \mathrm{Pr}(m)} = \frac{RF\mathrm{Pr}_m * (\partial + \mathrm{Pr}) - 2*(\mathrm{Pr}_m RF\mathrm{Pr}(m))}{(\delta + \mathrm{Pr})^2} = \frac{RF\mathrm{Pr}_m * (\partial - \mathrm{Pr}(m))}{(\delta + \mathrm{Pr})^2} \leq 0 \quad (22)$$

Probability of detection Pr (m) has to be greater than δ for condition (22) to yield the expected negative sign (negative impact of probability of detection on violation rate). This will hold true for larger values of Pr (m), implying that the higher the probability of detection, the lower the frequency of violation.

(4) Effect of discounting the future δ

$$\frac{\partial K}{\partial \delta} = \frac{-(p_a Q_m(E_m, s) - c - RF\mathrm{Pr}_m) * (\partial + \mathrm{Pr}(m)) + 2*(\mathrm{Pr}_m * (m * Pa * Qm - c * m) - RF\mathrm{Pr}(m)))}{(\delta + \mathrm{Pr})^2} \geq 0 \quad (23)$$

The non-negativity of result (23) is implied by the condition of optimality derived in Equation (18) for violating fishers, e.g. for m > 0. This result accordingly suggests that violation rate increases with higher discount rates, i.e. less important the future is for the violator who will prefer a given sum of money today to having the same amount in the future.

(5) Effect of the average price / returns from illegal catches P_a [7]

$$\frac{\partial V}{\partial p_a} = \frac{Q_m(E_m, s) * (\delta + \mathrm{Pr} - \mathrm{Pr}_m)}{(\delta + \mathrm{Pr})^2} \geq 0 \quad (24)$$

Taking into consideration the concave relation between *m* and *Pr(m)*, the value function *Pr(m)* ≥ its marginal value $Pr_m(m)$ at optimal levels of m, which implies non-negativity

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[7] Actually, the average price could be specified as $P_m\alpha + P_n(1-\alpha)$ where α is the proportion of small fish and 1-α is the proportion of normal fish. For simplicity we use P_a. The positive sign of equation 24 implies that the illegal proportion outweighs the legal one and hence increases the price of illegal nets per kg.

of result (24), suggesting that frequency of violation increases with higher prices of (returns from) an illegal (mixed) catch.

(6) Effect of fixed cost of the illegal net c

$$\frac{\partial V}{\partial c} = \frac{-\delta - \Pr + \Pr_m * m}{(\delta + \Pr)^2} = ? \qquad (25)$$

The effect of the fixed cost of the illegal net on violation rate that is specified by equation (25) is indeterminate. For this to yield the expected negative effect of a rise in the cost of acquiring the illegal net, the following must hold:

$$\Pr_m \prec (\partial + \Pr(m))/m \qquad (26)$$

Condition (26) simply requires that the incremental risk of being caught (marginal chance of detection) should be less than the average expected gains from not violating (opportunity cost of waiting for next period plus probability/opportunity of being caught) per violation attempt.

We compare the analytical results of this extended DDM using frequency measures with the results of earlier empirical studies in Table 1. It is clear that dynamic formulations have important advantages over static models, as they could control for the effects of key factors such as discounting the future, costs and prices. Analytical results derived with the extended DDM, which uses frequency measures, confirm the findings of an empirical DDM employing intensity measures for effects of key factors such as probability of fining (enforcement), level of fine and discount rate. Employing frequency instead of intensity, however, could sign the indeterminate effects of price of and income from illegal fishing and change in probability of detection. Dynamic formulation with frequency measures also gives more interesting economic meaning to the effects of and relationship between probability of detection and the social discount rate.

Table (1): Summary of the comparative statics' analyses for different models

Determinants of compliance/violation using intensity or frequency measures	**Static models using frequency measures [A]**	**Dynamic models using intensity measures [C]**	**Dynamic models using frequency measures (this study)**
Probability of fining (R)	Negative	Negative	Negative
Level of fine (F)	Negative	Negative	Negative
Probability of detection	Must be less than the fine [B]	Must exceed the fine	Must be higher than the discount rate to deter violation
Discount rate (δ)	Not included	Positive	Positive
Price of / income from illegal catch	Not included	Undetermined	Positive
Fixed cost of illegal fishing	Not included	Undetermined	Undetermined
Normative factors	Positive/negative	Positive	Not included

A. This group includes Furlong (1991), Kuperan and Sutenin (1994 and 1999), Hatcher *et al.* (2000), Hatcher and Gordon (2005), Kuperan and Sutenin (1998), King and Sutenin (2010)
B. Except for Furlong (1991)
C. This group includes Lueng (1994), Davis (1988), Akpalu (2008)

4. Summary and Conclusions

A number of factors related to market and institutional failures make frequency of non-compliance with regulation more suitable than intensity measures of violation in the artisanal fisheries of developing countries. Due to the fact that illegal catches are not sold on formal markets, it is very hard to estimate the total catch per day that includes violating harvests and hence presents a data problem. Also, employing frequency as a measure of violation rate provides the opportunity of capturing the direct link between violation rates and seasonality of illegal fishing (e.g. months of active breeding when quantities of small fish are high, which encourages illegal fishing). Use of frequency also helps to classify fishers into categories of violators, a typology that will help policy makers and managers design policy measures and instruments suited for each group.

Violation rates in fishery regulation, however, have so far been mainly specified only as "intensity" whereas "frequency of violation" has been used only in static deterrence models. The present study is the first to use frequency as a measure of violation rates in a dynamic formulation in spite of the proven advantages of using frequency over intensity measures in static deterrence models.

This paper accordingly extends the two times dynamic deterrence model (DDM) to use frequency instead of intensity of non-compliance as a measure of violation rate. The method of comparative statics is employed to derive analytical results on the sensitivity of optimal violation to a number of key factors of high relevance to compliance with regulation designed to protect against over fishing. Analytical results obtained with this extended DDM confirm the findings of earlier empirical studies employing alternative static and dynamic formulations and reveal more interesting economic meaning of modelled relations. The study concludes that in developing country artisanal fisheries where probability of detection, enforcement and levels of fine are typically low and poverty levels leading to high impatience about the future (discount rate), violation rates are bound to be high. The relative magnitude of the effects of each of these factors on compliance with regulation, however, remains an important empirical question that requires further investigation for prioritisation of policy actions.

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Annexure A: The dynamic deterrence with frequency of violation specification

Using definitions of legal and illegal profits (πm and πn) in equations 1 to 3, we simplify the value function for each violator $V(m,n,c,b,p_a,p_n,E_m,E_n,Q_m,Q_n,s,x)$ or $V(.)$ of equation (5) on page 8 as:

$$V(.) = \int_0^\infty e^{-\partial t}\{(\Pi m + \Pi n) * (1 - G(t)) + \Pi n * G(t) - RFg(t)\}dt \quad \text{(A1)}$$

$$V(.) = \int_0^\infty e^{-\partial t}\{(\Pi m + \Pi n - \Pi m * G(t) - RFg(t)\}dt \quad \text{(A2)}$$

Using G(t) = 1-e^{-Bt} and g(t) = B e^{Bt} and B=Pr(m) we simplify A2 to become:

$$V(.) = \int_0^\infty e^{-\partial t}\{(\Pi m + \Pi n - \Pi m * (1 - e^{-Bt}) - RFBe^{-Bt}\}dt \quad \text{(A3)}$$

$$V(.) = \int_0^\infty e^{-\partial t}\{(\Pi n + \Pi m * e^{-Bt}) - RFBe^{-Bt}\}dt \quad \text{(A4)}$$

$$V(.) = \int_0^\infty e^{-\partial t}\{\Pi n + (\Pi m - RFB)e^{-Bt}\}dt \quad \text{(A5)}$$

$$V(.) = \frac{\Pi n}{\partial} + \frac{\Pi m}{B + \partial} \quad \text{(A6)}$$

Which, in the expanded form, is:

$$V(.) = \frac{(p_a.m.Q_m(E_m, s) - cm)}{\Pr(m) + \delta} + \frac{(p_n.n.Q_n(E_n, x) - bn)}{\delta} \quad \text{(A7)}$$

Annexure B. Derivation of comparative statics' properties

Employing the first-order conditions' equation 16, which determine the optimal frequency of violation (i.e. m*) implicit in equation B1, we can derive the comparative statics' (CS) properties of m* with respect to its parameters (P_a, P_n, R, F, C, b and δ). Let K be

$$K = \frac{\partial V}{\partial m} = \frac{(p_a Q_m(E_m, s) - c - RF \Pr_m) * (\delta + \Pr) - \Pr_m (m(p_a Q_m(E_m, s) - c) - \text{RFPr(m)})}{(\delta + \Pr)^2} = 0 \quad \text{(B1)}$$

We simplify B1 using above definitions of πm and πn to:

$$K = \frac{\partial V}{\partial m} = \frac{(\Pi m_m - RF \Pr_m) * (\delta + \Pr) - \Pr_m (\Pi m - \text{RFPr(m)})}{(\delta + \Pr)^2} = 0 \quad \text{(B2)}$$

Where $\Pr_m$ is $\frac{\partial \Pr(m)}{\partial m}$ and πm_m is $\frac{\partial \Pi m}{\partial m}$

Invoking the Implicit Function Theorem for function K (m*(α), α), where α is a vector of the set of arguments in the model and m is at its optimal level m* (hence omitting the * for simplicity), the following holds for each argument α_j at the optimum (Chiang, 1984):

$$\frac{dK}{d\alpha_j} = \frac{\partial K}{\partial m} * \frac{\partial m}{\partial \alpha_j} + \frac{\partial K}{\partial \alpha_j} = 0 \text{, such that } \frac{\partial m}{\partial \alpha_j} = -\frac{\partial K}{\partial \alpha_j} / \frac{\partial K}{\partial m} \quad \text{(B3)}$$

From B1-B3, we get the following CS results:

(1) Probability of fining R (enforcement)

$$\frac{\partial K}{\partial R} = \frac{(-F \Pr_m) * (\delta + \Pr) + \Pr_m F \Pr(m)}{(\delta + \Pr)^2} = \frac{F \Pr_m * (-\delta - \Pr + \Pr)}{(\delta + \Pr)^2} = \frac{-F \Pr_m \delta}{(\delta + \Pr)^2} < 0 \quad \text{(B4)}$$

D4 has to yield a negative value since the denominator is +ve and F, $\Pr_m$(m) and δ are all +ve values ($\Pr_m$(m) is +ve by the assumption of concavity of Pr(m) function, e.g. hazard rate is increasing in frequency of violation m). This result ($\frac{\partial K}{\partial R} < 0$) together with the satisfaction of the second order conditions of value function V(.), which implies that $\frac{\partial K}{\partial m} < 0$, imply that $\frac{\partial m}{\partial R} = -\frac{\partial K}{\partial R} / \frac{\partial K}{\partial m} < 0$ (B5)

Result (B5) implies that violation rate – frequency (optimal m) decreases with an increase in the probability of paying a fine if detected (R).

(2) Level of fine

$$\frac{\partial K}{\partial F}=\frac{(-R\Pr_m)*(\delta+\Pr)+\Pr_m R\Pr(m)}{(\delta+\Pr)^3}=\frac{R\Pr_m*(-\delta-\Pr+\Pr)}{(\delta+\Pr)^3}=\frac{-R\Pr_m\delta}{(\delta+\Pr)^3}<0 \qquad \text{(B6)}$$

Following the same argument as above (denominator is +ve and R, $\Pr_m(m)$ and δ are all +ve values), it is clear that $\frac{\partial K}{\partial F}<0$. Again, together with value function's conditionality (that $\frac{\partial K}{\partial m}<0$), result B5 implies that frequency of violation (optimal m) decreases with an increase in the amount of the fine (F).

(3) Probability of detection Pr(m)

$$\frac{\partial K}{\partial \Pr(m)}=\frac{RF\Pr_m*(\partial+\Pr)-2*(\Pr_m RF\Pr(m))}{(\delta+\Pr)^3}=\frac{RF\Pr_m*(\partial-\Pr(m))}{(\delta+\Pr)^3}\leq 0 \qquad \text{(B7)}$$

For Result B7 to yield the expected negative sign (negative impact of probability of detection on violation rate), Pr(m) has to be greater than δ. This will hold true for larger values of Pr(m), implying that the higher the probability of detection, the lower is the frequency of violation.

(4) Discount rate

$$\frac{\partial K}{\partial \delta}=\frac{-(p_a Q_m(E_m,s)-c-RF\Pr_m)*(\partial+\Pr(m))+2*(\Pr_m*(m*Pa*Qm-c*m)-RF\Pr(m)))}{(\delta+\Pr)^3}\geq 0 \qquad \text{(B8)}$$

The non-negativity of result (B7) is implied by the condition of optimality derived in Equation 18 for violating fishers (e.g. for m > 0). Result (B8), accordingly, suggests that violation rate increases with higher discount rates, i.e. the less important the future.

(5) Return from violation (price of illegal catch)

$$\frac{\partial V}{\partial p_a}=\frac{Q_m(E_m,s)*(\delta+\Pr)-\Pr_m*m*Q_m(E_m,s)}{(\delta+\Pr)^3}=\frac{Q_m(E_m,s)*(\delta+\Pr-\Pr_m)}{(\delta+\Pr)^3}\geq 0 \qquad \text{(B9)}$$

Concavity of Pr(m) implies that the value function Pr(m) ≥ its marginal value $\Pr_m(m)$ at optimal levels of m, which implies non-negativity of result (B9), which suggests that frequency of violation increases with higher prices of (returns from) anillegal (mixed) catch.

(6) Fixed cost of illegal net - c

$$\frac{\partial V}{\partial c} = \frac{-\delta - \Pr + \Pr_m * m}{(\delta + \Pr)^2} = ? \qquad \text{(B10)}$$

Result (B10) is indeterminate. For this to yield the expected negative effect of cost of acquiring the illegal net, the following must hold:

$$\Pr_m \prec (\partial + \Pr(m))/m \qquad \text{(B11)}$$

Condition (B11) simply requires that the incremental risk of being caught (marginal chance of detection) should be less than the average expected gains from not violating (opportunity cost of waiting for next period plus probability/opportunity of being caught) per violation attempt.