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Abstract

The presence of illegal, unregulated and unreported (IUU) fishing activities is considered a serious barrier to the sustainable use of marine resources. This paper uses a game theoretic approach to investigate the strategic interaction between fishers and management in the presence of IUU fishing. Managers choose a combination of fines, inspection probabilities and whether to classify a firm as *group 1* or *group 2*, to induce a target level of compliance from fishers who choose whether or not to comply. Importantly, this paper finds that equilibrium compliance strategies of fishers affect stock levels over time. In particular, even using less than perfect monitoring and enforcement can lower illegal harvesting, which is beneficial for stocks. The paper further shows that increasing the cost of engaging in illegal activities, through punishment, may be a sound economic policy. The results, however, suggest that the punishment should be bounded in order to achieve the purpose for which it is intended.

JEL Classification: *C7, Q2, Q22*

Key words: *IUU fishing, game theoretic approach, inspection, violation and compliance, punishment, fish biomass, sustainability*

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1 Introduction

The presence of destructive and illegal fishing activities is a major threat to sustainability of fisheries. Any type of fishing practice or activity that violates fisheries regulatory measures is considered illegal. Such activities may include unauthorized by-catch, discard, exceeding allowable quotas, the use of explosives, and the use of unauthorized fishing equipment such as unauthorized mesh-sizes, and others. Illegal activities are common and sometimes reach extreme proportions (Clark, 1985), and have been identified as a serious threat to the marine ecosystem.[1] The consequences of illegal, unregulated, and unreported (IUU) fishing activities have become a global concern in recent years.[2] IUU fishing is found to contribute to the underestimation of catch and effort, undermine management programs, affect fish habitat, and is an inherently unsustainable fishing practice.

The need to control fishing effort and combat IUU activities requires the attention of fisheries managers around the world. In fact, Munro (1992) emphasizes that the problem of resource uncertainty requires that effort must be made to control fishing effort, and consequently harvest, in order to ensure some form of conservation and sustainability. According to Gordon (1954) one basic goal of fisheries management is to ensure that the benefits which the fisheries are capable of producing for society are neither wasted nor dissipated. The validity of Gordon's point has been shown many times in the real world.[3] A basic challenge in fisheries, however, is finding a balance between economic efficiency, conservation and sustainability of the resource.

This paper examines the strategic interaction between fishers and management in the presence of IUU fishing with respect to output regulations. Specifically, the paper uses a game theoretic approach to consider the firm's choice of legal and illegal

[1]The severity of the problem is well documented in the literature. See for example Pet-Soede and Erdmann, 1998; Halim and Mous, 2006; Costello and Guinness, 2010

[2]Details on this including the managerial and sustainability consequences can be found in Ostrom, 1990; Charles and Cross, 1999; Pitcher and Guenette, 2002; Stokke, 2009, Pitcher and Guenette, 2002, Pauly, 1989; FAO, 2002.

[3]Munro (1992) provides real world examples to show the validity of Gordon's point.

effort to maximize profit in response to the fisheries manager's choice of regulation, in the form of a harvest quota, and enforcement as: fines, inspection probabilities, and group classification. The interaction is modeled as a two-person dynamic game which gives rise to a steady-state equilibrium. This equilibrium characterizes the less-than-perfect enforcement strategy of the manager in response to the firms' compliance and violation behaviour. In addition, it allows consideration of the dynamic effect on fish stocks.

We show that fines, inspections and group classification, if properly applied, are important instruments that may help reduce the negative impact of illegal effort in fishing activities. The results also suggest that firms optimally choose the strategy of *violate* when in group 1 (where inspection probability is lower), and *comply* when assigned to group 2 (where inspection probability is higher). Firms' illegal activities have been shown to place less value on the future of fisheries by using a discount factor higher than that which will ensure sustainable harvest over time. The marginal product of the fishery is also eroded by the consequences of firms' illegal behaviour when adopting illegal strategies to maximize economic profit. It must be noted that contrary to empirical evidence suggesting increasing maximum penalties considerably (Ostrom, 1990), the theoretical results in this paper indicate that punishment should have upper bound if it is to achieve the purpose for which it is intended. It is also argued that the compliance model developed in the paper, though based on individual fishing quota assumptions, is applicable and important under various systems of fisheries management as far as conservation and sustainability issues are concerned.

The application of game theoretic concepts to investigate various issues of management is not uncommon in fisheries economics.[4] What is uncommon, as far as we are aware, however, is the application of such concepts in the study of regulatory enforcement and compliance in fisheries economics. In theory the question of mon-

[4]For examples and details on these applications in fisheries see Munro, 1979, 1987; Sumaila, 1995; Jachmann and Billiouw, 1997; Trisak, 2005; Kronbak and Lindroos, 2007; Keane et al., 2008

itoring and enforcement in fisheries management studies remains largely ignored.[5] Considering enforcement in the fisheries as a two-person game is consistent with theory, as done by Harrington (1988) in the emission regulation context, for example.[6] Harrington applies game theory in environmental regulation as applied in the tax literature.

Enforcement can be difficult and costly, but if ignored the entire management system can be grossly endangered.[7] Studies in illegal hunting, for instance, show that enforcement effort increases the incidence of poaching which negatively impacts wildlife population (Keane et al., 2008). Regulatory enforcement, through monitoring and punishment when violation is detected, is considered an integral part of successful conservation and natural resource management. The effect of enforcement designs on various management control systems in fisheries, forestry, wildlife poaching and, other conservation policies cannot succeed if managers are not able to influence behaviour of natural resource users (Jachmann and Billiouw, 1997; Ostrom, 1990; De Merode et al., 2007). Importantly, regulatory enforcement is found to be a necessary mechanism to solve a commons dilemma over time (Gibson et al., 2005).

The paper draws heavily on Harrington (1988) but also differs in a number of ways. Harrington (1988) investigates the dynamics of compliance and violation in relation to compliance cost. This paper, on the other hand, examines the effect of punishment on profits as the major determinant of compliance. Furthermore, whereas Harrington (1988) assumes the size of punishment in any period to be restricted, this paper assumes the size of punishment in any given period of the interaction is dependent on size of violation. These assumptions help to incorporate the underlying dynamics

[5]Charles and Cross (1999); Gibson et al. (2005); Coelho and Pedro (2008), provide evidence to suggest that theoretical investigation of monitoring and enforcement in fisheries management remains uncommon.

[6]Similar applications can be found in Raymond (1999), Harford (1991, 2000), and Eckert (2004). These studies have considered the strategic role of environmental regulation and compliance, and have found that compliance is greater when violations are likely to be costly.

[7]Long and Flaaten (2011), and Clark (1985) analyze the efficiency, conservation and management challenges facing the resource.

of fishery, particularly the dynamics of the fish stock.

To effectively analyse the effect of firms' effort choices on stock levels, it is important to understand why even firms that regularly comply may choose to violate at one time or the other. Moral and social considerations, besides economic gains, play a significant role in fisher decisions. The subgroup of profit maximizers, on whose behaviour social influence and moral obligation have little or no effect, may well account for the majority of violators (Kuperan and Sutinen, 1998). A firm may violate if it is losing money and there is potential to derive benefits from violation. This economic motive increases the probability of violation. The greed factor is also identified in the literature as a reason accounting for violation. The urge to increase profit even when already making profits can be a driving force for violation.[8] Besides the rent-seeking behaviour, over-capacity is also identified as a major economic cause of illegal fishing. In fact, subsidies that contribute to the maintenance, development, or transfer of fishing capacities are likely to artificially reduce the cost of IUU fishing capacities, both locally and internationally (Le Gallic and Cox, 2006). Cheap and ready labour in developing countries reduces operational costs and, in some circumstances, reduces the real cost of risk for vessel owners who are able to abandon and replace arrested crew members easily and at low cost (Agnew and Barnes, 2004).[9]

The rest of the paper proceeds as follows. Section 2 describes the model, detailing the interaction between the manager and the firms, and the transition movements between groups. Section 3 discusses firms' effort choices when complying or violating in a single period under different management systems, and the consequences of this strategy given management enforcement instruments. Section 4 investigates a dynamic case of the violate and comply strategy. Section 5 concludes the paper, highlighting some policy implications of the strategic interaction between management and fishing firms.

[8]Issues on how economic incentives override social and moral obligations and, increase the incidence of violation are well documented in the literature, including; Charles and Cross (1999) and Ostrom (1990).

[9]Indonesia, China, and the Philippines, are cited examples of sources of IUU crews in recent times.

2 The Model

The model considers interactions among the fisheries manager and $N \geq 2$ risk-neutral fishing firms.[10] The players interact a finite number of times. We use Harrington (1988)'s set-up to study monitoring and enforcement of renewable resource management using output restrictions. We investigate the relationship between a firm's 'compliance' profit and the average level of compliance when both enforcement budget and the maximum penalty are limited, and further look at firms' profits when complying and when violating.

It is assumed that any illegal fishing activity increases catch levels above some allowable quota, $\bar{h}$. For ease of analysis a non-transferable individual quota (IQ) regime is assumed. We consider N firms with fixed capital, who have identical marginal cost, c, in competitive market setting. Firms take the biomass, B, in each period as given.

This Section investigates a steady-state equilibrium in a dynamic game with two groups, two players and two possible actions. Subsection 2.1 explains the manager's problem, Subsection 2.2 explains the firm's problem in any given period. Here profit maximizing behaviour of firms within an output controlled regulatory environment with imperfect inspection is explained. Subsection 2.3, before characterizing the dynamic model, explains the transition movements. The fisheries managers enforcement strategy is then investigated in Subsection 2.4.

2.1 The fisheries manager

At the start of any period the manager sets an individual fishing quota, $\bar{h}$, the maximum allowable harvest level for that period. Fishers may choose to conduct illegal activities of catching an additional $h^{'}$ above the legal amount, giving a total harvest of $h = \bar{h} + h^{'}$. At the beginning of the game, the manager separates all the fishers

[10]Throughout this paper, 'fishing firms', 'firms' and 'fishers' are used interchangeably to mean the same thing.

into two groups, G_1 and G_2. In every period, the manager has the following actions: *inspect,* or *not inspect.* It is assumed the manager chooses the probabilities μ_i of inspecting firms in Group i ($i = 1, 2$) The inspection probabilities are chosen so that the conditions $\mu_2 > \mu_1$ and $\mu_2 + \mu_1 = 1$, always hold.[11] This means the manager would inspect a firm in group 2 more often than he/she would inspect a firm in group 1. In addition, it is also assumed that the probability of inspection is not affected by the incidence of a violation.[12] If the manager inspects a firm and discovers a violation, then that firm pays a penalty/fine and is moved to G_2 if in G_1, or remains in G_2 with certainty if already in G_2. If the manager inspects a firm and finds that it is complying, the firm is moved to G_1 with probability η (< 1), if in G_2, as a form of reward, or remains in G_1 with certainty if already in G_1.

Previous work including Charles and Cross (1999), De Merode et al. (2007) and Becker (1968) distinguish between the probabilities of inspection, detection and punishment, that is, not all firms who are *violating* are caught or punished if inspected. This paper does not make this assumption. Instead, it is assumed here that once a firm is inspected a violation is detected without error. It is also assumed that a *violating* firm pays the fine,

$$F = fh^{'}$$

if convicted. The scale of fine, $f > 1$, is chosen by the manager to give firms with highest compliance cost incentive to comply.[13] The fine increases with $h^{'}$, the level

[11] $\mu_1 = [0, 1)$ and $\mu_2 = (0, 1]$.

[12] Note that the definition of inspection probabilities in this paper differs from Harrington (1988), where μ_1, and μ_2, are chosen randomly and the condition above is not imposed. In the current definition the firm knows before hand what the inpection probability would be in any given group and makes a decison, whether to violate or comply, accordingly.

[13] In this formulation it is assumed the occurrence of a violation can either be detected or suspected off site, thus raising the probability of an inspection. Here the firm is certain about the value of punishment it faces once caught, and factors that into its profit-maximizing behaviour when violating. This also means that the size of violation is dictated by the effect of punishment on expected profit since size of punishment is known in advance. This is as opposed to $F = \theta h^{'}$, which is based on the assumption that everyone is inspected but violation is detected with some probability, θ. In this formulation there is no certainty about size of punishment if managers do not announce in advance what the inspection probability would be. Furthermore, since this formulation

of illegal activity. $F = fh^{'}$, means that under risk neutrality assumption not every firm is inspected, but once inspected violation is detected and punished.

The general economics of crime and punishment shows that risk-neutral individuals will only engage in a criminal activity if and only if their private expected gains exceed the expected sanctions for doing so (Becker, 1968; Stiegler, 1971). The specific structure of penalties, since Becker (1968), has thus been considered important determinant of crime rate. Becker (1968) indicates that violators' [criminals] expectation of gains from illegal activity has to be countered by an expectation that some violators are caught and punished.[14] From the assumption of regulatory imperfection, not all violators are punished, especially first time violators. This means that only some violating firms are likely to be punished.

The manager's overall objective is to maximize the sustainable value of the fishery. Within this, with respect to enforcement, the manager's objective is to minimize frequency of violation, subject to fixed enforcement budget. The probability of inspection, μ_i, and the probability of being transfered, η, are chosen to minimize the average inspection rate in steady-state to reduce inspection cost. The manager maximizes the target compliance rate in steady-state, and chooses the scale of the punishment/fine, f.

2.2 The firms

A firm chooses whether to comply (c) or violate (v) with a set of regulations. It is assumed that firms' violating behaviour is to increase harvest by $h^{'}$ above the allowable quota, $\bar{h}$, in a given fishing period. Firms complying earn 'compliance' profit, π_c, while those violating earn 'violation' profit, π_v. Firms internalize penalties

is also based on the assumption that punishment is restricted, firms may not care about how much they violate given that cost is the only concern. This does not fit well in the fishery's case where stock dynamics are a major concern of managers. In Harrington (1988) F is not given explicit definition.

[14] Green and McKinlay (2009), is an example where first time violators are unlikely to be punished.

for violating regulations like any operational cost. Were the manager to announce in advance what the inspection probability would be, a firm's optimal behaviour is non-random. The firm in that case is better off complying with certainty (that is, with probability 1) if $\pi_c > \pi_v - \mu_i F$, and violating otherwise, assuming that μ_i and F are large enough. Firms take other firms' actions, as well as the stock level, B, as given. Price, p, and harvesting costs are also taken as given under competitive market conditions. The analysis uses a harvesting function: $h = qeB$, where q is catchability coefficient, e is the fishing effort, and B is the fish biomass. In a given period all firms complying earn the same profit. This profit is referred to as 'compliance' profit, π_c, and is given by:

$$\pi_c = (pqB - c)e \tag{1}$$

The cost of harvesting is simply ce, where c is the constant managerial cost of effort. It is important to note that compliance profit is the same whether the firm is group 1 or group 2, that is, $\pi_{1c} = \pi_{2c} \equiv \pi_c$.

Let the allowable quota, $\bar{h}$, be defined as: $\bar{h} = qe^L B$, where e^L and B, are legal effort and the fish stock, respectively. Defining harvest above $\bar{h}$ as $h^{'} = h - \bar{h}$, let $h = e^{IL}qB + qe^L B$, and $h^{'} = e^{IL}qB$, where e^{IL} is illegal effort. The assumption is that when firms violate they choose some amount of illegal effort in addition to legal effort. Hence total effort when violating is defined as: $e^T = e^{IL} + e^L$. This means that under compliance firms' total effort will be equal to legal effort; that is, $e^T = e^L \equiv e$. For group 1 firms violating, the 'violation' profit, exclusive of expected fine, will be:

$$\pi_{1v} = (pqB - c)e^L + (pqB - c)e^{IL} \tag{2}$$

and they will pay a fine, if inspected, with expected value of $\mu_1 f qBe^{IL}$.[15] Similarly,

[15] In reality not all violators are punished, especially first time violators (Green and McKinlay, 2009).

the profit for group 2 firms violating, exclusive of expected fine, can be expressed as:

$$\pi_{2v} = (pqB - c)e^{L} + (pqB - c)e^{IL}, \tag{3}$$

but the expected value of the fine will be $\mu_2 f qBe^{IL}$, which is higher than the value of group 1 firms' expected fine. In line with Harrington (1988) it must be observed here that in static analysis the fisheries manager and firms do not have a way of reacting to each other's actions since the game is one shot game. Given expected penalty as a function of rate of violation the firms make a single choice of violate or comply.

2.3 Description of transition movements (two state model)

In this set up, a two-state model in which firms are moved between groups based on their compliance history is assumed. A firm found complying in G_2 upon inspection is returned to G_1 with probability, η (< 1). Thus the firms and the manager are players in a pair of linked games with payoff matrices shown in Table 1 below.

Table 1: Payoff matrices for the enforcement game

	Group 1 (G_1)		*Group* 2 (G_2)	
	Comply	Violate	Comply	Violate
No inspection $(1-\mu_1,\, 1-\mu_2)$	π_{1c}	π_{1v}	π_{2c}	π_{2v}
Inspection $(\mu_1,\, \mu_2)$	π_{1c}	$\pi_{1v} - F$ $\longrightarrow G_2$	π_{2c} $p(\rightarrow G_1)=\eta$	$\pi_{2v} - F$

A firm violating in G_1 achieves profit π_{1v} if there is no inspection. Notice that $\pi_{1v} > \pi_{1c}$ because a violating firm's harvest is greater than that of a complying firm, that is, $h > \bar{h}$. However, if there is inspection a firm violating in G_1 receives π_{1v} but is also punished with a fine, F, and moved to G_2 with certainty. If there is inspection a firm complying in G_2 earns compliance profit and a chance, $p(\rightarrow G_1) = \eta$, of being moved to G_1. This inspection and enforcement process poses a Markov decision problem for the firm (Kohlas and Schmidt, 1982; Harrington, 1988). Strategies are independent of history and are only conditional on which group the firm is in. More generally a firm's movement from group to group is according to transition probabilities that depend on the current group and the firm's action taken in that period; that is, comply or violate. Further, a firm's payoff in each period is dependent on the group and the action taken. In the following matrix firms' transition probabilities, $\mu_i^{[a]}$, are described. The superscript $[a = 0, 1]$ indicates a firm's action comply, or violate, respectively, and $i = 1, 2$, as earlier defined.

Table 2: Matrices describing the transition probabilities $\mu_i^{[a]}$

	Comply ($a = 0$)		Violate ($a = 1$)	
	G_1	G_2	G_1	G_2
G_1	1	0	$1 - \mu_1$	μ_1
G_2	$\mu_2\eta$	$1 - \mu_2\eta$	0	1
	Panel (a)		*Panel* (b)	

From panel (a) of Table 2, observe that a G_1 firm complying remains in G_1 with certainty, that is, probability 1. In other words, the probability of moving a G_1 firm which is complying, to G_2, is 0. Panel (b), on the other hand, shows that the probability of a G_1 firm violating, and remaining in G_1 or being moved to G_2 is $1-\mu_1$ or μ_1, respectively. The probabilities of a G_2 firm's movements between groups is explained analogously.

Let S_{mn} be the strategy space from which a firm in G_i adopts a specific strategy $s_{mn} \in S_{mn}$ to optimize its payoff following a specific action by the fisheries manager. Here the subscripts, $m\,n$, take on discrete values 0 or 1 and denote the actions: comply or violate, in different groups. The manager's action is a specific regulation or set of regulations. In this setting a *decision* at any period is a mapping from groups to actions, and a strategy [policy] is a sequence of decisions over time. A strategy

s_{mn} for the firm is a mapping $s_{mn} : \{G_1, G_2\} \rightarrow \{0,\ 1\}$; i.e., a mapping of groups into decisions either to comply or violate a regulation or set of regulations. Notice that in any two given periods of the game, firms in either group can decide to do the following: comply (C) in both groups; comply, when in group 1 and violate (V), in group 2; violate in group 1 and comply in group 2; or violate in both groups. For the firms in the two groups, Table 3 summarizes the compliance strategy described here.[16] Next we consider firms' expected profits and analyse their strategic behaviour in a dynamic setting.

Table 3: Firms Strategy matrix

Strategy	G_1	G_2
s_{00}	C	C
s_{01}	C	V
s_{10}	V	C
s_{11}	V	V

2.3.1 Firms' expected profit functions in the dynamic model

Before analyzing firms' strategic behaviour in detail, firms' expected profits following their response to the manager's inspection and penalties is explained. Let $E^{mn}[\pi_{G_i}]$ be the discounted present value of expected profit of a firm, i, when in G_i adopting a strategy s_{mn}. Profits are discounted with discount factor, β; where, $0 \leq \beta < 1$. Assuming that firms' profits follow a stationary process over time, the expected present value of a firm in G_1 adopting strategy s_{00}, is the profit when complying this period, plus the discounted expected present value in the next period. This is expressed as:

[16]The actions: C, C − comply in both groups; C, V − comply in group 1 and violate in group 2; V, C − violate in group 1 and comply in group 2; and V, V − violate in both groups. This paper makes the following observation. As Harrington (1988) rightly points out, the degree of noncompliance is important in real world situations where the occurrence of certain violations is continuous; for example, in the case of environmental pollution. However, in this model a firm makes discrete choices; comply, or violate.

$$E^{00}[\pi_{1c}] = \pi_{1c} + \beta E^{00}[\pi_{1c}] \quad (4)$$

Similarly, by the stationary property, the expected present value of a firm in G_2 adopting strategy s_{00}, is expressed as;

$$E^{00}[\pi_{2c}] = \pi_{2c} + \mu_2\eta\beta E^{00}[\pi_{1c}] + (1-\mu_2\eta)\beta E^{00}[\pi_{2c}] \quad (5)$$

This means that the expected profit, in present value, of a G_2 firm adopting strategy s_{00}, is the profit when complying in current period, plus the expected profit discounted one period when; either transferred to G_1 and complying or remaining in G_2 and complying. For strategy s_{11}, using the stationary property assumption, the expected profit, in present value, of a G_1 firm violating in both groups is expressed as:

$$E^{11}[\pi_{1v}] = \pi_{1v} - \mu_1 F + \mu_1\beta E^{11}[\pi_{2v}] + (1-\mu_1)\beta E^{11}[\pi_{1v}] \quad (6)$$

This is to say that the expected profit, in present value, of a G_1 firm adopting strategy s_{11} is the profit when violating in current period minus the punishment, plus the expected profit discounted one period when: either transferred to G_2 and violating or remaining in G_1 and violating. The expected profit, in present value, of a G_2 firm adopting strategy s_{11}, by the stationary property, is analogically expressed as:

$$E^{11}[\pi_{2v}] = \pi_{2v} - \mu_2 F + \beta E^{11}[\pi_{2v}] \quad (7)$$

The four sets of simultaneous equations giving the present values of strategies s_{00}, s_{01}, s_{10} and s_{11} are stated in the matrix in Table 4.

Table 4: Matrix of firms' expected profits when complying or violating

	Comply (0)	Violate (1)
G_1 :	$E[\pi_{1c}] = \pi_{1c} + \beta E[\pi_{1c}]$	$E[\pi_{1v}] = \pi_{1v} - \mu_1 F + \mu_1\beta E[\pi_{2v}] + (1-\mu_1)\beta E[\pi_{1v}]$
G_2:	$E[\pi_{2c}] = \pi_{2c} + \mu_2\eta\beta E[\pi_{1c}] + (1-\mu_2\eta)\beta E[\pi_{2c}]$	$E[\pi_{2v}] = \pi_{2v} - \mu_2 F + \beta E[\pi_{2v}]$

Solving these simultaneous equations gives the present values of the strategies.[17] Unless essentially required for explanation, superscripts may sometimes be dropped for convenience. It was earlier established that $\pi_{1c} = \pi_{2c} \equiv \pi_c$, thus π_{1c}, and π_{2c}, are replaced with π_c.

2.3.2 Solution summary

To discuss the Lemmas that follow from the solutions to the equations in Table 4 we first provide a summary of the solutions in Table 5. The Table shows expected profits for each of the four strategies firms in each group adopt.[18]

Table 5: Firm expected profits for different strategies

Strategy	$E^{ij}[\pi_{G_1}]$	$E^{ij}[\pi_{G_2}]$
s_{00}	$\frac{\pi_c}{1-\beta}$	$\frac{\pi_c}{1-\beta}$
s_{01}	$\frac{\pi_c}{1-\beta}$	$\frac{\pi_{2v}-\mu_2 F}{1-\beta}$
s_{10}	$\frac{\beta\mu_1\pi_c + (\pi_{1v}-\mu_1 F)[1-\beta(1-\mu_2\eta)]}{(1-\beta)[1-\beta(1-\mu_1-\mu_2\eta)]}$	$\frac{\pi_c[1-\beta(1-\mu_1)] + \beta\mu_2\eta(\pi_{1v}-\mu_1 F)}{(1-\beta)[1-\beta(1-\mu_1-\mu_2\eta)]}$
s_{11}	$\frac{(1-\beta)(\pi_{1v}-\mu_1 F) + \mu_1\beta(\pi_{2v}-\mu_2 F)]}{(1-\beta)[1-\beta(1-\mu_1)]}$	$\frac{\pi_{2v}-\mu_2 F}{1-\beta}$

Lemma 1. *Strategy s_{01} is not optimal.*[19]

When $\pi_c > \pi_{2v} - \mu_2 F$, a firm's best response is to comply in both groups since it is more costly to violate in G_2, which means s_{00} is preferred to s_{01}. When $\pi_c <$

[17] The Appendix (A.1) explains how the expected profits in Table 4 are derived.
[18] See Appendix A for derivations.
[19] The proof is in Appendix A

$\pi_{2v} - \mu_2 F$, a firm is better off violating in both groups G_1 and G_2, which means s_{11} is preferred to s_{01}. This means strategy s_{01} is never optimal.

The underlying assumption of Lemma 1, is that firms are rational and violation is motivated by rent-seeking behaviour. This means if punishment makes violation costly and compliance is more profitable then a firm's preference would be to comply in both groups 1 and 2, satisfying the first statement explaining Lemma 1. On the other hand, under the given assumption, a firm violates if and only if gains from violation, given punishment, exceed gains from compliance. In that case a firm's preference is to violate in both groups G_1 and G_2, satisfying the second statement.

Next, consider the expected profits of a firm in group i, $E^{mn}[\pi_{G_i}]$, of the remaining strategies as functions of compliance profit, π_c, in the form $A+B\pi_c$. Let the expected profit of a firm in group 1 which always complies be expressed as; $E^{00}[\pi_{G_1}]$: $A = 0$, and $B\pi_c = \dfrac{\pi_c}{1-\beta}$, that is, $B = \dfrac{1}{1-\beta}$, and $\beta \neq 1$ implying $B > 0$; similarly the expected profit of a firm which violates when in group 1 and complies when in group 2 is expressed as; $E^{10}[\pi_{G_1}]$: $A + B\pi_c$; implying $A > 0,\ B > 0$; and the expected profit of a firm which violates when in group 1 and violates when moved to group 2 is expressed as; $E^{11}[\pi_{G_1}] : A + B\pi_c$; implying $A > 0,\ B = 0$.

Lemma 2. *Firms are indifferent between strategies s_{00} and s_{10}.*[20]

Setting either $E^{00}[\pi_{G_1}]$ to $E^{10}[\pi_{G_1}]$, or $E^{00}[\pi_{G_2}]$ to $E^{10}[\pi_{G_2}]$ and solving for π_c an expression for L_0, the leverage or expected profit from violation, is obtained. For $L_0 \equiv \pi_c$, that is complying when $\pi_c = \pi_{1v} - \mu_1 F \equiv L_0$, it can be established that $E^{00}[\pi] = E^{10}[\pi] > E^{11}[\pi]$. This means that payoffs to strategies s_{00} and s_{10} become identical and firms are indifferent between the two.

[20] The proof is in Appendix A

Based on the assumption made under Lemma 1, a firm violates in any future period if expected profit from violation exceeds expected profit from compliance in any given group. This implies that when expected profits from any two strategies are identical a firm is indifferent between such strategies. In this case when expected profit from the strategy of complying in G_1 and G_2 is identical to the expected profit from the strategy of violating in G_1 and complying in G_2, the firm would be indifferent between the two strategies.

Let us now investigate what happens in other strategy cases by solving for compliance profit, π_c, and analyzing the leverage, L, as before. Solving for π_c by either equating $E^{10}[\pi_{G_1}]$ to $E^{11}[\pi_{G_1}]$, or $E^{10}[\pi_{G_2}]$ to $E^{11}[\pi_{G_2}]$, and expressing the result as L_1 the following is obtained:

$$L_1 \equiv \pi_c = (\pi_{2v} - \mu_2 F) - \frac{\beta\mu_2\eta[(\pi_{1v} - \mu_1 F) + (\pi_{2v} - \mu_2 F)]}{1 - \beta(1 - \mu_1)}. \quad (8)$$

It can be verified that when $L_1 \equiv \pi_c < \pi_{2v} - \mu_2 F$, $E^{10}[\pi] = E^{11}[\pi] > E^{00}[\pi]$.[21] This means that when expected profit from violation in G_2 is greater than expected profit from compliance, then expected profit from the strategy of violating in G_1 and complying in G_2, is equal to the expected profit of the strategy of violating in both G_1 and G_2, and greater than the expected profit from the strategy of complying in G_1 and G_2.

Summary of a firm's optimal strategy choices, ϕ, can be given as follows:

$$\phi = \begin{cases} s_{00} \quad if \quad \pi_{1v} - \mu_1 F \leq L_0 \\ \\ s_{10} \quad if \quad L_0 \leq \pi_{1v} - \mu_1 F \leq L_1, \\ \\ s_{11} \quad if \quad L_1 \leq \pi_{1v} - \mu_1 F \end{cases}$$

Given that $\mu_2 F > \mu_1 F$, L_1 must be at least less than $\pi_{2v} - \mu_2 F$, the expected payoff

[21]See derivations in Appendix A.

when a firm violating in G_2 is punished. In degenerate cases the following will occur:
(a) L_1 will equal π_{2v}, when there is no inspection in G_2, that is, when $\mu_2 = 0$;
(b) L_1 will equal $\pi_{2v} - \mu_2 F$, when $\beta = 0$ (perfect myopia);
(c) L_1 will equal $\pi_{2v} - \mu_2 F$, when $\eta = 0$, that is, when firms complying in G_2 are not rewarded with transfers to G_1;
(d) L_1 will equal $\pi_{2v} - \mu_2 F$, when $\pi_{2v} - \pi_{1v} = 0$, and $\mu_1 F - \mu_2 F = 0$.[22]

In all other cases $L_1 < \pi_{2v} - \mu_2 F$, must hold. Thus firms are classified as s_{00}, s_{10}, or s_{11} firms, based on their optimum strategies which also depend on their 'compliance' profits and the enforcement parameters chosen by the manager. Given the probability that an s_{mn} firm is in compliance is λ_{mn}, a firm complies with probability $\lambda_{00} = 1$, and violates with probability $\lambda_{11} = 0$. A firm choosing strategy s_{10} violates in G_1 and complies in G_2. This strategy presents an interesting case because a firm is in compliance only part of the time. When this strategy, s_{10}, is optimum the transition matrix in Table 6 can be observed.

Table 6: Firms' transition matrix

Group	G_1	G_2
G_1	$1 - \mu_1$	μ_1
G_2	$\mu_2 \eta$	$1 - \mu_2 \eta$

With this strategy a firm violates when in G_1, but complies in G_2. The frequency of compliance in steady-state is the stationary probability of being in G_2, given as: $\lambda_{10} = \dfrac{\mu_1}{\mu_1 + \mu_2 \eta}$.

In steady-state the manager inspects firms adopting strategy s_{ij} with probability ψ_{ij}. Firms complying in both groups G_1 and G_2 are inspected with probability $\psi_{00} = \mu_1$, and those violating in both groups are inspected with probability $\psi_{11} = \mu_2$. In

[22]From Equations (2) and (3) it can be verified that when $\pi_{2v} - \pi_{1v} = 0$, $\mu_1 F - \mu_2 F = 0$.

steady-state s_{00} firms are in G_1 with certainty. Strategies s_{00} and s_{11} are absorbing states; firms in these states remain there forever. Likewise, firms with strategy s_{11} are in G_2 with certainty. It follows that in steady-state the manager inspects firms with s_{10} strategy in either state with probability,

$$\psi_{10} = \frac{\mu_2\eta}{\mu_1 + \mu_2\eta}\mu_1 + \frac{\mu_1}{\mu_1 + \mu_2\eta}\mu_2 = \frac{\mu_1\mu_2(1+\eta)}{\mu_1 + \mu_2\eta}.$$

This equation can be explained as the probability that a firm is in group 1, multiplied by the probability of inspection in group 1, plus the probability of the firm being in group 2, multiplied by the probability of inspection in group 2. Notice that for $\lambda_{00} = 1$, and $\lambda_{11} = 0$, it can be observed that $\lambda_{00} > \lambda_{10} > \lambda_{11}$. Also, for $\psi_{00} = \mu_1$, $\psi_{11} = \mu_2$, and $\mu_1 < \mu_2$, it implies that $\psi_{00} < \psi_{10} < \psi_{11}$. This means firms with good compliance history are inspected less.

2.4 Fisheries manager's enforcement strategy

This Section analyses the fisheries manager's enforcement strategy. Since enforcement is costly, the manager's goal is to minimize resources employed in monitoring and enforcement, while achieving a target compliance rate. To do this, the manager may want to modify the following four parameters: the inspection frequencies μ_1 and μ_2, the probability of transfer η, and the fine, $\mathcal{F}$. This boils down to ensuring that the leverage or expected profit from violation, L_1 (earlier defined), is as low as possible in order to achieve a target compliance rate.

This property of the manager's enforcement policy is also referred to as the leverage (Harrington, 1988), but defined differently from the firm's leverage. The leverage in this case is defined as follows. Suppose that for any given violation there is a maximum allowable penalty, $\mathcal{F}^{max}$. Let Ω be the steady-state target compliance rate. Let Π_c be the set of all compliance profits such that $\pi_c \in \Pi_c$, and any firm with profit $\pi_c^{max} \in \Pi_c$, where $\pi_c^{max} = \textit{lower upper bound of } \Pi_c$, complies with probability Ω.

Let us also define Π_v as the set of all violation profits for firms violating, such that $\pi_v \in \Pi_v$, with $\pi_v^{max} = \textit{lower upper bound of } \Pi_v$, and $\triangle = \pi_v^{max} - F^{max}$, where $\triangle$ defines the leverage of the enforcement policy for the compliance rate, Ω. To achieve perfect compliance (i.e., for $\Omega = 1$) the manager must ensure that $F^{max} > \pi_v^{max}$. This is to say that in equilibrium the manager aims at perfect compliance and so modifies the inspection frequencies, μ_1 and μ_2, together with the probability of transfer reward η, in order to ensure that equilibrium maximum punishment exceeds equilibrium maximum violation profit. The assumption here is that there is no compliance if maximum '*violation*' profit, less discounted maximum future penalties, exceeds maximum compliance profit (i.e., $\pi_v^{max} - F^{max}/(1-\beta) > \pi_c^{max}$). In the next paragraph we show that some amount of compliance is achievable even when this assumptuion is violated. We also set up the manager's optimization problem to minimize average inspection rate in equilibrium even when this assumption is violated.

In Section 4 of this paper, it is argued that some firms, for various reasons, are not deterred by punishment/penalties and therefore violate even when making losses. It can, however, be shown that some amount of compliance is achievable even if maximum violation profit, after accounting for discounted maximum future penalties, is negative, that is, $\pi_v^{max} - F^{max}/(1-\beta) < 0$. From $L_1 \equiv (\pi_{2v} - \mu_2 F) + \dfrac{\beta\mu_2\eta[\pi_{2v} - \pi_{1v} + \mu_1 F - \mu_2 F]}{1-\beta(1-\mu_1)}$, the leverage discussed earlier, it can be noted that if $F = F^{max}$, $\mu_2 \approx \eta = 1$, and $\mu_1 = \varepsilon$, where ε is sufficiently small value such that $\varepsilon \in (0,\ 1)$, then

$$L_1 \equiv \pi_{2v} - F^{max} + \frac{\beta[\pi_{2v} - \pi_{1v} + \varepsilon F^{max} - F^{max}]}{1-\beta(1-\varepsilon)} = \frac{\pi_{2v}(1+\varepsilon\beta) - \beta\pi_{1v}}{1-\beta(1-\varepsilon)} - \frac{F^{max}}{1-\beta(1-\varepsilon)}.$$

If maximum violation profits in both G_2 and G_1 are equal, that is, if $\pi_{2v} = \pi_{1v} \equiv \pi_v^{max}$, then $L_1 \equiv \pi_v^{max} - \dfrac{F^{max}}{1-\beta(1-\varepsilon)}$. Given that ε is sufficiently small, this result implies that L_1 can be as close as possible to $\pi_v^{max} - F^{max}/(1-\beta)$, that is, $L_1 \approx \pi_v^{max} - F^{max}/(1-\beta)$. If the manager's target compliance rate, Ω, in steady-state is such that $\Omega < 1$ and for some $\pi_v^{max} < F^{max}/(1-\beta)$, some amount of compliance is feasible, then the manager's optimization problem is to minimize ψ_{10} with respect to μ_1, μ_2, F, and η, that is[23]

$$\underset{\{\mu_1,\ \mu_2,\ F,\ \eta\}}{Min\ \psi_{10}} = \frac{\mu_1\mu_2\,(1+\eta)}{\mu_1+\mu_2\eta}$$

subject to

$$L_1 = \pi_{2v} - \mu_2 F + \frac{\beta\mu_2\eta[\pi_{2v} - \pi_{1v} + \mu_1 F - \mu_2 F]}{1-\beta(1-\mu_1)} \le \pi_c$$

$$\lambda_{10} = \frac{\mu_1}{\mu_1+\mu_2\eta} \ge \Omega$$

$$0 \le F \le F^{max}$$

2.4.1 Results

In this Section two important results from the manager's optimization problem are analysed. From the results compliance profit, π_c, and compliance rate, Ω can be stated as:

$$\pi_c = \pi_{2v} - \mu_2 F + \frac{\beta\mu_2\eta[\pi_{2v} - \pi_{1c} + \mu_1 F - \mu_2 F]}{1-\beta(1-\mu_1)} \tag{9}$$

and

$$\Omega = \frac{\mu_1}{\mu_1+\mu_2\eta} \tag{10}$$

It can be seen from Equation (9) that at the optimum the leverage, $\pi_c \equiv L_1$. Thus,

[23] See Appendix A for derivations

the punishment F, should be chosen in such a way that it should not be profitable to violate. In other words, F should be such that gains from violation should not exceed gains from compliance. It can also be observed from Equation (10) that compliance rate is solely determined by group inspection probabilities, μ_1 and μ_2, and the transfer reward η. One implication of this is that compliance rate, Ω, rises when inspection probability in group 1, μ_1, is increased while increasing inspection probability in group 2, μ_2, as well as rises in tranfer reward, η, reduce compliance rate. Equation (9) shows that at the optimum the leverage, $L_1 = \pi_c$. Thus, the punishment F, should be chosen in such a way that it should not be profitable to violate. In other words, F should be such that gains from violation should not exceed gains from compliance.

To see this observe the following. From Equation (10) notice that a unit increase in inspection probability in group 1, μ_1, results in a positive increase in compliance rate (i.e., $\dfrac{\partial \Omega}{\partial \mu_1} = \dfrac{\mu_2 \eta}{\mu_1 + \mu_2 \eta} > 0$). It is also easy to see that marginal increases in μ_2 and η, on the other hand, lead to marginal decrease in compliance rate, respectively (i.e., $\dfrac{\partial \Omega}{\partial \mu_2} < 0$ and $\dfrac{\partial \Omega}{\partial \eta} < 0$). This means that in equilibrium the manager is better off doing the following: increasing the inspection probability in group 1 (where firms are violating because they know, before hand, that inspection in this group is lesser); reducing the probability of inspection in group 2 (where firms are complying with the hope of being rewarded with a transfer to group 1 where they can violate); and reducing the probability of transfer reward from group 2 to group 1 (since this is only an incentive for firms to get the chance to violate in group 1). Notice also that in trying to minimize the equilibrium average inspection rate, ψ, the fisheries manager does not achieve perfect compliance, that is, $\Omega \neq 1$, and that there is an extent to which inspection in group 2, μ_2, can be reduced in equilibrium. These and other observations are examined next.

We examine the possibility of achieving perfect compliance as well as the extent of possible reduction of inspection probability, μ_2, in group 2. First let Equation (8) be re-arranged as: $L_1 = \pi_{2v} - \mu_2 F + \dfrac{\beta\mu_2\eta[(\pi_{2v} - \mu_2 F) - (\pi_{1v} - \mu_1 F)]}{1 - \beta(1 - \mu_1)}$. If in equilibrium maximum violation profits, π_v^{max}, in both groups are the same for all firms violating, as earlier indicated, and that from Equation (4), $\pi_{2v} - \mu_2 F = \pi_{1v} - \mu_1 F$, then the above relation implies $\pi_{2v} - \mu_2 F \leq L_1$. Given that $\beta \leq 1$, by setting $\beta = 1$, L_1 can be re-written as:

$$L_1 = \pi_{2v} - \mu_2 F + \frac{\mu_2\eta(\pi_{2v} - \mu_2 F)}{\mu_1} - \frac{\mu_2\eta(\pi_{1v} - \mu_1 F)}{\mu_1},$$

and

$$\pi_{2v} - \mu_2 F \leq [\pi_{2v} - \mu_2 F]\left(1 + \frac{\mu_2\eta}{\mu_1}\right) - \frac{\mu_2\eta(\pi_{1v} - \mu_1 F)}{\mu_1} = [\pi_{2v} - \mu_2 F]\left(\frac{\mu_1 + \mu_2\eta}{\mu_1}\right) - \frac{\mu_2\eta(\pi_{1v} - \mu_1 F)}{\mu_1}.$$

Let us recall that in steady-state the stationary probability of being in G_2, is: $\lambda_{10} = \dfrac{\mu_1}{\mu_1 + \mu_2\eta}$. Then letting $\dfrac{\mu_1 + \mu_2\eta}{\mu_1} = \dfrac{1}{\lambda_{10}}$, and $\lambda_{10} \geq \Omega$, the following is established:

$$\pi_{2v} - \mu_2 F \leq \frac{\pi_{2v} - \mu_2 F}{\lambda_{10}} - \frac{\mu_2\eta(\pi_{1v} - \mu_1 F)}{\mu_1} \leq \frac{\pi_{2v} - \mu_2 F}{\Omega} - \frac{\mu_2\eta(\pi_{1v} - \mu_1 F)}{\mu_1}$$

$$\Longleftrightarrow$$

$$\pi_2 - \mu_2 F \leq \frac{\pi_{2v} - \mu_2 F}{\lambda_{10}} \leq \frac{\pi_{2v} - \mu_2 F}{\Omega}.$$

From here the following important results are established.
Result 1: Inspection has lower bound.
Result 2: Optimum compliance can not be perfect.

Proof of Result 1.

Let $(\pi_{2v} - \mu_2 F)\Omega \leq \pi_{2v} - \mu_2 F$ *and* $\pi_{2v}(\Omega - 1) \leq \mu_2 F(\Omega - 1)$, yielding $\mu_2 \geq \dfrac{\pi_{2v}}{F}$.

For $\pi_{2v} = \pi_v^{max}$, $F = F^{max}$, and $\pi_v^{max} < F^{max}$, observe that $\mu_2 \geq \dfrac{\pi_v^{max}}{F^{max}}$. This means that inspection in G_2, at the optimum is greater than or equal $\frac{\pi_v^{max}}{F^{max}}$, and cannot be set below $\frac{\pi_v^{max}}{F^{max}}$. Recalling that $\mu_2 = (0,\, 1]$, notice that if $\pi_v^{max} = F^{max}$, then μ_2 can only take on a minimum value of 0, thus proving Result 1.

The implication of Reult 1 is that even though reducing inspection in group 2 in equilibrium is desirable (see earlier disciussion in this section) beyond a given lower bound any further reduction in μ_2 is not optimal.

Proof of Result 2.

From Equation (8) let $(\pi_{2v} - \mu_2 F)\Omega \leq \pi_{2v} - \mu_2 F$. This implies that $\Omega \leq 1$. But, as earlier noted, if $\pi_v^{max} < F^{max}$, then $(\pi_v^{max} - \mu_2 F^{max})\Omega < \pi_v^{max} - \mu_2 F^{max}$, yielding $\Omega < 1$. This shows that at the optimum compliance can not be perfect (i.e. $\Omega \neq 1$), satifying Reult 2.

Result 2 implies that even though management would expect to observe perfect compliance from all firms, compliance cannot be perfect in equilibrium. From Equation (7) observe that perfect compliance in equilibrium is achievable only if inspection of group 2 firms, μ_2, and, or transition probability, η, are reduced to zero. As observed from Result 1, inspection of group 2 firms in equilibrium has a lower bound and so setting μ_2 to zero is not optimal. In additon since the transition probability, η, is an incentive to induce firm compliance setting it to zero is costly.

We have discussed the interaction between the manager and the firms under different strategies, together with the transition movements. Next we investigate the possible consequence of these strategies and interactions in specific fisheries cases. In Section 3 we consider firms' effort choices when complying or violating under different management regimes given management enforcement instrument in a single period. In this static case firm movements between groups, as an incentive instrument, do not apply; firms have inspection and punishment only. This is followed by analysis under a dynamic case in Section 4. In this scenario we consider the optimal equilibrium strategy, S_{10}, discussed in Section 2, again in a specific fisheries setting.

3 Firms' Effort Choices when Complying or Violating: A Static Case

In this Section a single period, static case, is used to illustrate how illegal fishing and enforcement enter the standard fisheries model. Specifically, the Section examines the effect of illegal effort choices on harvest, profit, and stock levels in a single period, given inspection and punishment as enforcement instruments. Given the fisheries manager's target levels, firms' effort choices when either complying or violating in a single period will have varying effects on stock, harvest and profit levels. We consider the effect of firms' effort choices on these variables when firms comply or violate in any single period. In this case, it is assumed all firms are in equilibrium, and are all either complying or violating. The effects of these choices are examined under individual fishing quota (IFQ or simply IQ) and maximum economic yield scenarios. We start by identifying a number of management regimes in fisheries, and then focus on the non-transferable individual quota management regime.

3.1 Management regimes

Management regimes in fisheries range from open access (common property); total allowable catch (TAC) without fishing rights; TAC with fishing rights allocated to a number of fishers (limited licenses); TAC with fixed percentage shares (property rights as allocation of catch shares, also known as individual fishing quota or individual quota, IQ); and, individual transferable quotas (ITQs), with full property rights.[24]

[24] IFQ or IQ gives property rights in a given fishing period. This is neither a permanent ownership nor transferable right and may be lost upon leaving the industry, or retirement. IFQ, unlike ITQ, falls short of providing full property rights. ITQ owners have full property rights to fixed shares of the fishery, with transferable rights. The main distinction between IQ and ITQ is the transferability

Open access has been found to lead to over exploitation of the stocks, leading to possible collapse or extinction of some species (Clark, 1973). TAC, without allocation among fishers (no property right), if not properly monitored with full enforcement may lead to overcapacity with negative consequences on profits and stock. Limited licenses is equally found to result in 'Olympic' fishing with the attendant adverse effect on stocks. IQ though is meant to address the 'race-to-fish' phenomenon and overcapacity issues, lack of incentives could compromise stock levels even under this regime. Besides other reasons, detailed later, fishers or fishing firms planning to retire or go out of business may be motivated to engage in illegal fishing activities. In other words, since IQ does not offer its holders transferable rights these owners may not have the incentive to conserve the stock for the future.[25] The model developed in this Section investigates the strategic interaction between fishers and management in the presence of illegal, unregulated, and unreported (IUU) fishing, under individual fishing quota (IFQ, or simply IQ) and maximum economic yield scenarios.

Catch monitoring and reporting is argued to deserve more attention in current policy processes focused on establishing property rights.[26] This emphasizes the argument that the model developed in this paper, though based on individual quota (IQ) management system, is applicable and important under various management systems in fisheries, as far as profit maximization, conservation, and sustainability issues are concerned.

element (Nowlis and Van Benthem, 2012).

[25]Arnason (1990) and Grafton (1996) argue that when fishers do not view their quota as exclusive and permanent harvesting rights they face short-term incentives, thus removing the uniform incentive among participants and lobby for value-maximizing TAC.

[26]Nowlis and Van Benthem (2012) argue that the belief that individual transferable quota management systems (ITQs) prevent fisheries collapse may not be correct in widely adopted class of fisheries models, and that monitoring is essential in the policy argument for property rights in fisheries.

3.2 Effort choices under quota management regime when complying

It is important to investigate the firm's behaviour, in terms of effort choices under non-transferable individual quota (IQ) management system. Under the IQ system we assume that in any given period a firm may choose to comply or violate a management policy on allowable quota. Theory shows that the private owner of the fishery would not allow effort to expand beyond maximum sustainable yield effort (Crutchfield and Zellner, 1962; Munro, 1992). It is, therefore, assumed in this Section that the manager is 'naive' and believes firms are not violating by employing illegal effort to harvest more than allowed under IQ management system.[27] The maximum economic yield (MEY) case is, therefore, examined.

Taking the first derivative of total revenue, TR, and total cost, TC, with respect to effort, the marginal revenue and marginal cost of the firms are defined. Expressing TR and TC respectively as $TR = pqBE$, and $TC = cE$, and making the necessary substitutions the partial derivatives of TR and TC with respect to effort, E, are expressed as: $\frac{\partial TR}{\partial E} = \frac{\partial TC}{\partial E}$, the equivalent of MR and MC, respectively. This expression also implies that marginal revenue and marginal cost are equal, and expressed as: $MR = MC$. The maximum economic yield effort and stock levels are also found to be;

$$E_{MEY} = \frac{r}{2q}\left(1 - \frac{c}{pqK}\right)$$

and

$$B_{MEY} = \frac{K}{2}\left(1 + \frac{c}{pqK}\right),$$

respectively. The maximum economic yield harvest and firms' profit, given as; $H_{MEY} = qB_{MEY}E_{MEY}$, and $\pi_{MEY} = pH_{MEY} - cE_{MEY}$, after the necessary substi-

[27]'Naive' here is used to describe the manager who believes there is no illegal activities or violations of the regulations, and therefore does no inspection. This assumption is relaxed later in Section 3.3.

tutions are derived as:

$$H_{MEY} = \frac{rK}{4}\left[1 - \left(\frac{c}{pqK}\right)^2\right]$$

and

$$\pi_{MEY} = \frac{r}{4q}\left[\frac{(pqK - c)^2}{pqK}\right] = \frac{rpK}{4}\left[1 - \frac{c}{pqK}\right]^2,$$

respectively.

Observe from the E_{MEY} , the H_{MEY}, and the π_{MEY} expressions here that increases in cost reduce profits and so the profit maximizing firm reduces effort and, consequently harvest, in order not to reduce profits. The effect of this profit maximizing behaviour is that the biomass, B_{MEY}, under maximum sustainable yield, increases as cost rises. Notice that under the IQ system profit is not zero. The manager expects the firms to ensure that rent continues to be positive.

3.3 Effect of effort choices when violating

In this Section it is assumed that the manager is not naive and believes firms may have incentives to employ illegal effort to increase harvest. The manager therefore uses inspection and punishment as incentive instruments to deter firms from violating. The consequences of such violation under IQ, specifically the effect of firms' effort choices on harvest and stock levels, are studied.

Given that the profit motive may well account for the majority of violators, the focus of this paper, thus, is to investigate firms' behaviour where rent-seeking is the sole motivating factor when engaging in illegal harvesting. In a sense, this is a worst-case scenario where firms violating are considered amoral profit maximizers. As before, groups 1 and 2 firms violating are denoted as '$1v$' and '$2v$' respectively. Recall that the fisheries manager inspects firms in these two groups with different inspection rates; that is, group 1 firms are inspected with μ_1, while group 2 firms are inspected with μ_2. These firms also receive different punishments when violating. For group 1 firms the punishment is $\mu_1 f h'$ and the chance of being moved to group 2, and for group 2 firms the punishment is $\mu_2 f h'$.

3.3.1 Group 1 firms' effort choices when violating under maximum economic yield

In Section 2 we made the assumption that firms in both groups choose legal and illegal effort when violating. Given this assumption the firms maximize profit by choosing illegal effort, E^{IL}, subject to biomass being sustainable. We state the problem of group 1 firms violating, in a static case, and analyse the effect of the firms' effort choices under maximum economic yield (MEY). Let the profit of group 1 firms violating be given by:

$$\underset{E^{IL}}{Max}\, \pi_{1v} = \left[(pqB - c)\, E^{L} + (pqB - c - \mu_1 f q B)\, E^{IL}\right] \tag{11}$$

subject to

$$B = K\left(1 - \frac{q}{r}[E^{L} + E^{IL}]\right)$$

$$B \geq 0; \quad E^{IL} \geq 0$$

Taking the first order condition of Equation (11) with respect to illegal effort, E^{IL}, and re-arranging we find the static equilibrium level of illegal effort. Notice that we take the first derivative with respect to illegal effort because firms are deliberately choosing illegal effort and so it is more interesting to analyse the effects of this choice. We establish the static equilibrium level of illegal effort as:

$$E^{IL}_{1v\,(MEY)} = \frac{r}{2q}\left[1 - \frac{c}{qK(p - \mu_1 f)}\right] - \frac{1}{2}\left[\frac{p}{(p - \mu_1 f)} + 1\right] E^{L}_{1v\,(MEY)} \tag{12}$$

Similarly, the illegal effort chosen by group 2 firms violating can also be expressed as:

$$E^{IL}_{2v\,(MEY)} = \frac{r}{2q}\left[1 - \frac{c}{qK(p-\mu_2 f)}\right] - \frac{1}{2}\left[\frac{p}{(p-\mu_2 f)} + 1\right] E^{L}_{2v\,(MEY)} \tag{13}$$

Here it can be observed that for firms in both groups punishment and cost are the most significant determinants of effort choices. We explain this below.

Starting with punishment. From Equations (12) and (13) notice that for firms in both groups violating as $\mu f \rightarrow p$, holding all else constant, $E^{IL}_{MEY} \rightarrow -\infty$. This is because the terms in the last brackets of the equations approach negative infinity as marginal punishment gets closer to marginal gains. The result is that legal effort, E^{L}_{MEY}, as a component of total effort increases infinitely. In other words, as illegal effort virtually disappears legal effort increases, which is a desirable outcome. It is worth noting, however, that it is not optimal for punishment to exceed marginal benefit. When punishment exceeds marginal benefit (i.e., when $\mu f > p$) illegal effort grows infinitely positive (i.e. $E^{L}_{MEY} \rightarrow +\infty$). This may well explain the earlier argument that firms making losses, for example, may continue to violate knowing that vessels and cheap labour can be easily replaced when caught and punished (Agnew and Barnes, 2004).

Next we look at the effect of cost. It can be observed from the first brackets in the two equations that as $\mu f \rightarrow p$, holding all else constant, the negative effect of cost, c, on illegal effort explodes, driving illegal effort down towards negative infinity. This can be interprted to mean that as punishment wipes away any gains from illegal effort, cost of operations becomes so large that no illegal effort is chosen. Significant increases in the carrying capacity of the biomass, K, on the other hand, may increase illegal effort, all else being equal.

We analyse the maximum economic yield stock level, B_{MEY}, by substituting for E^{IL}_{MEY} in the stock function, B, above and simplifying to obtain the following expression for the MEY stock level for group 1 firms violating:

$$B_{1v\,(MEY)} = \frac{K}{2}\left[\left(1 + \frac{c}{qK[p - \mu_1 f]}\right) + \frac{1}{r}\left(\frac{pq}{[p - \mu_1 f]} - 1\right) E^{L}_{1v\,(MEY)}\right]$$

Similarly for group 2 firms violating MEY stock level can also be expressed as:

$$B_{2v\,(MEY)} = \frac{K}{2}\left[\left(1 + \frac{c}{qK[p - \mu_1 f]}\right) + \frac{1}{r}\left(\frac{pq}{[p - \mu_2 f]} - 1\right) E^{L}_{2v\,(MEY)}\right]$$

It is clear that for a set amount of effort, B_{MEY} is positively related to legal effort, E^{L}_{MEY}, and cost, c. Again, the effect of punishment here is similar to that discussed earlier. For both groups 1 and 2 firms violating, as $\mu f \to p$, $B_{MEY} \to +\infty$, significant increases in cost increases stock levels, monotonically. Further to that, observe that when punishment exceeds marginal benefit, that is, $\mu f > p$, the impact on stock levels is negative, emphasising the point made earlier that punishment should have upper bound. Expressing MEY harvest level as $H_{MEY} = qB_{MEY}\left[E^{L}_{MEY} + E^{IL}_{MEY}\right]$, it is easy to see that illegal effort increases harvest, holding all else constant. This further explains the reduction in stock levels with increases in illegal effort, E^{IL}_{MEY}.

4 Firms' Effort Choices when Complying or Violating: A Dynamic Case

This Section evaluates the full dynamic model when firms are in equilibrium playing optimal strategies; violate in group 1 and then comply in group 2 (i.e., the s_{10} strategy).[28] In Section 3.2 it was observed that firms in this game have three optimal strategies; s_{00}, s_{10}, or s_{11}, that is, comply when in either group, violate when in group 1 and comply in group 2, or violate when in either group, respectively. In Section 2 it was also argued that strategies s_{00}, and s_{11} do not present interesting

[28] The derivation of all first order conditions, and the algebra in this Section are presented in Appendix B

cases for analysis. This is further confirmed by Sections 3, where it was shown that both groups 1 and 2 firms are likely to violate for one reason or another, and so there is no rational justification to expect that in reality all firms will comply. This means that though strategy s_{00} may have interesting theoretical interpretation, firms' effort choices may not present useful practical insights and so it is not pursued further. For strategy s_{11}, if it is obvious that firms are going to choose to violate in each state, then management's solutions could be straightforward, though not necessarily simple.

A more interesting case from a practical perspective is the non-absorbing strategy, s_{10}. Firms adopt this optimal strategy because they know it is costly to violate when in G_2 where they face more frequent inspection and, as a result, larger expected punishment. It is optimal for firms to comply in G_2, and get promoted to G_1 where violation is less costly for them. Recalling from Table 5, let us denote a firm's equilibrium profit for strategy s_{10} as π_{10}:

$$\begin{aligned}\pi_{10} &= \frac{1}{A}\left[\beta\pi_c + (\pi_{1v} - \mu_1 f h^{'})[1-\beta(1-\psi\eta)]\right] \\ &= \frac{1}{A}\left[\beta\pi_c + (\pi_{1v} - \mu_1 f q B e^{IL})Q\right]\end{aligned}$$

where; $A = (1-\beta)[1-\beta(1-\mu_1-\mu_2\eta)]$, and $Q = [1-\beta(1-\mu_1\eta)]$. Substituting for π_c and π_{1v}, as previously defined, gives the following total equilibrium profit function:

$$\pi_{10} = \frac{1}{A}\left((\beta+Q)[pqB-c]E^L + (pqB-c-\mu_1 f q B)E^{IL}Q\right).$$

From this equation let the total revenue TR_{10}, and total cost, TC_{10}, functions be defined respectively as:

$$TR_{10} = \frac{1}{A}\left[\beta\left(pqB+qB\right)QE^L + (pqB)QE^{IL}\right]$$

and

$$TC_{10} = \frac{1}{A}\left[(\beta+Q)cE^L + (c+\mu_1 f q B)QE^{IL}\right].$$

4.1 Maximum economic yield under strategy: violate, comply

To analyse firms' effort choices under maximum economic yield (MEY) when adopting the optimal strategy s_{10} in equilibrium, we first substitute the expression for the stock, B, into the expressions for total revenue, TR_{10}, and total cost, TC_{10}. We then take their respective first order conditions (FOCs) with respect to illegal effort, E^{IL}. We do so because firms adopting strategy s_{10} choose illegal effort, taking legal effort, E^L, as given. When firms are adopting strategy s_{10} choice of illegal effort presents a more compelling case for analysis. This is so because illegal effort has been shown earlier in Section 3 to have negative impact on both legal effort and stock levels. From the FOCs the level of illegal effort choice when firms adopt strategy s_{10} is determined as:

$$E^{IL}_{MEY} = \frac{r}{2q}\left(1 - \frac{c}{qK(p-\mu_1 f)}\right) - \frac{1}{2}\left[1 + \frac{(\beta+Q)p}{Q(p-\mu_1 f)}\right] E^{L}_{MEY}.$$

The above equation shows the inverse relation between legal and illegal efforts under *MEY*. This relation shows that an increase in either legal or illegal effort leads to a decrease in the other, all else being equal.

The impact of punishment on illegal effort is also observed. It is clear from the above equation that as punishment, $\mu_1 f$, approaches marginal gains, p, legal MEY effort, E^L_{MEY}, approaches infinity, and forces illegal MEY effort, E^{IL}_{MEY}, to approach negative infinity. If the last part of the right hand side of the above equation is ignored, the strong impact of punishment on illegal effort is still observable. As punishment approaches marginal benefit, cost increases monotonically, and creates a strong and negative impact on illegal MEY effort, that is, as $\mu f \to p$, $c \to \infty$, resulting in $E^{IL}_{MEY} \to -\infty$. So here, as in the case observed in Section 3.3, significant increases in cost and punishment reduces illegal effort significantly, with resulting positive impact on stock levels. Again, it is confirmed that marginal punishment should not exceed marginal gains/benefit, that is, $\mu_1 f \ngtr p$, since this only serves to increase illegal effort as observed in the above equation. The consequences of firms' profit maximization are examined next.

4.2 Profit maximization under strategy: violate, comply

This Section investigates the profit maximizing objective of the firm, over time, when; complying and violating. The outcome in each case is then compared with the Fisheries manager's expectation as a benchmark. The discussion starts with the Fisheries manager.

4.2.1 No illegal fishing benchmark

In any given period the fisheries manager would expect that firms will choose only legal effort to maximize their profits. This means given a profit function of the form $\pi_t = (pqB_t - c)E_t$, the manager's objective function can be stated as:

$$\underset{\{\ E_t\ \}_{t=0}^{\infty}}{Max} \int_0^{\infty} e^{-\delta t} \pi_t \left(B_t,\ E_t\right) dt$$

subject to

$$\dot{B}_t = rB_t \left(1 - \frac{B_t}{K}\right) - qB_tE_t$$

$$B_t \geq 0; \quad E_t \geq 0$$

where B_t, the stock at time t, is the state variable and E_t, the effort at time t, is the choice or control variable. Setting up the Hamiltonian and taking the FOCs, the manager's expected effort choice for all firms, $E^{\star}$, in steady-state, and the modified golden rule *(MGR)* of the resource stock accumulation are respectively derived as:

$$E^{\star} = \frac{r}{q}\left(1 - \frac{B^{\star}}{K}\right)$$

and

$$\delta = r\left(1-\frac{2B^\star}{K}\right)+\frac{r}{n}\left(1-\frac{B^\star}{K}\right)\frac{c}{pqB^\star - c},$$

where $B^\star$ is the stock level in steady-state.[29] The MGR is sometimes referred to as the economic return, at the margin, on investment in the resource. Notice that when $c = 0$, the social discount factor, δ, is equal to the marginal return on the stock due to the growth function, i.e. $\delta = r\left(1-\frac{2B^\star}{K}\right) \equiv F^{'}(B^\star)$. This means it is worthwhile for the fisheries manager to ensure that sustainable harvest, at the margin, is equal to the social discount factor. On the other hand, when $\delta = 0$, it can be observed that $F^{'}(B^\star) < 0$, i.e. a situation where the marginal product of the Fishery resource is negative. Next, we analyse firms' profit maximizing behaviour as a case of IUU.

4.2.2 Firms' behaviour under violation

From earlier discussions, it has been noted that firms undertaking illegal unreported and unregulated (IUU) activities are violating a regulation or set of regulations. It was further indicated that firms do so by employing illegal effort, e_t^{IL} at any time, t. In Section 2 it was established that one interesting equilibrium behaviour of the firm is to choose strategy s_{10}. This discussion is continued here by examining the firm's profit maximizing behaviour when adopting this strategy in any given period. As before, N competing firms in the fishery at time t are considered. A firm choosing strategy s_{10} chooses illegal effort, e_t^{IL}, over and above the legal effort, e_t^{L}. The firm in this case faces a possible punishment of magnitude, $\mu_1 fqB_te_t^{IL}$. The firm's profit function can then be expressed as: $\pi_t = pqB_t(e_t^L+e_t^{IL})-c(e_t^L+e_t^{IL})-\mu_1 fqB_te_t^{IL}$. Firm i optimizes its profit, taking into account effort choices of its competitors. Defining $e_t^L + e_t^{IL} \equiv e_t^T$ as a firm's total effort at time t, firm $i's$ profit maximizing behaviour

[29]See proof in Appendix C.

is characterized by the following optimization problem:

$$\underset{\left\{ e_{it}^{T} \right\}_{t=0}^{\infty}}{Max} \quad \int_{0}^{\infty} e^{-\delta t} \left\{ pqB_t e_{it}^{T} - ce_{it}^{T} - \mu_1 f q B_t (e_{it}^{T} - e_{it}^{L}) \right\} dt$$

subject to

$$\dot{B}_t = rB_t \left(1 - \frac{B_t}{K}\right) - qB_t((e_{it}^{L} + e_{it}^{IL}) - \sum_{j \neq 1} q_t B_t((e_{jt}^{L} + e_{ijt}^{IL})$$

$$B_t \geq 0; \quad e_{it}^{T} \geq 0$$

Again, assuming all j other firms to be identical, making the necessary assumptions, and taking the FOCs of the Hamiltonian gives the firm's steady-state effort choices and the MGR, when violating, respectively as:

$$\overline{e}^{T} = \frac{r}{nq}\left(1 - \frac{\overline{B}}{K}\right)$$

and

$$\delta = r\left(1 - \frac{2\overline{B}}{K}\right) - \frac{r}{n}\left(1 - \frac{\overline{B}}{K}\right)\left[\frac{q(n-1)(p-\mu_1 f)\overline{B} - nc}{q\overline{B}(p-\mu_1 f) - c} - \frac{q^2\overline{B}\mu_1 f\,\overline{e}^{IL}}{q\overline{B}(p-\mu_1 f) - c}\right]$$

In this case when $c = 0$, $\delta = \frac{r}{n}\left[1 - (n+1)\frac{\overline{B}}{K}\right] + \frac{\mu_1 q f\,\overline{e}^{IL}}{p - \mu_1 f}$.[30] This is to say that the discount factor increases by the level of illegal activities in the fishery. This means IUU activities place less value on the future of the fishery. Firms violating discount the future heavily, and any investment in the fishery is eroded. This is emphasized

[30]See proof in of Appendix C.

even when $\delta = 0$. When $\delta = 0$,

$$r\left(1 - \frac{2\overline{B}}{K}\right) = \frac{r}{n}\left(1 - \frac{\overline{B}}{K}\right)\left[\frac{q(n-1)(p-\mu_1 f)\overline{B} - nc}{q\overline{B}(p-\mu_1 f) - c} - \frac{q^2\overline{B}\mu f e^{IL}}{q\overline{B}(p-\mu_1 f) - c}\right],$$

showing that marginal product of the fishery is eroded mainly by the consequences of firms' illegal behaviour when adopting strategy s_{10} to maximize economic rent.

Possible reasons accounting for illegal behaviour have been discussed earlier. It is, however, important to emphasise that another plausible reason for such myopic behaviour among IQ owners could be the lack of permanent ownership rights under the system. In other words the lack of transferability rights under the IQ system could be disincentive to preserve the stock, and not to discount the future heavily, particularly for retiring fishers or firms planning to leave the fishery. This echoes views expressed by Arnason (1990) and Grafton (1996). In the case of ITQ, however, the greed factor mentioned earlier could be a major reason for engaging in illegal activities that are likely to erode any future benefits that may accrue from increases in stock levels. Another reason is that if individual quotas mean there is excess capacity that trading cannot help redistribute, then the cost of undertaking some illegal effort may be relatively small (i.e., marginal cost of illegal effort is only viareaible cost). This also confirms the assertion of Nowlis and Van Benthem (2012) that, the belief that ITQ management systems prevent fisheries collapse may not be entirely correct.

5 Concluding Remarks

Destructive and illegal fishing activities are found to be a major threat to conservation and sustainability of the fisheries industry. Activities such as discard, the use of explosives, exceeding allowable quotas, unauthorized by-catch, and others, violate fisheries regulatory measures and are therefore considered illegal. Such illegal, unreported, and unregulated (IUU) fishing activities have been shown to contribute to underestimation of catch and effort. IUU fishing undermines management programs, affect fish habitat, and is an inherently unsustainable fishing practice. This paper sought to investigate the strategic interaction between fishers and management in the presence of IUU, and the possible effect of such interaction on the fish biomass.

We used a game theoretic approach to examine the firm's choice of legal and illegal effort to maximize profit in response to the fisheries manager's choice of regulation, in the form of harvest quota, and enforcement as; fines, inspection probabilities, and group classification. The interaction between fishers and management was modeled as a two-person dynamic game which gives rise to a steady-state equilibrium. This equilibrium characterized the less-than-perfect enforcement strategy of the manager in response to the firms' compliance and violation behaviour. In addition, the interaction allowed consideration of the dynamic effect on fish stocks. To effectively analyse the effect of firms' effort choices on stock levels, it was important to understand why even firms that regularly comply may choose to violate at one time or the other. We assumed rent-seeking behaviour as the main motivation for violation, and that any illegal effort increased catch levels above the allowable quota and consequently impacted the biomass negatively.

Results show that optimal compliance cannot be perfect, and that inspection has a lower bound. Even though management would expect to observe perfect compliance from all firms, compliance cannot be perfect in equilibrium. To achieve perfect compliance in equilibrium would require reducing the inspection of group 2 firms or the transition probability of a group 2 firm to group 1 to zero. Inspection of group 2 firms in equilibrium was shown to have a lower bound and so setting it to zero in equilibrium is not optimal. In other words, even though reducing inspection of group 2 firms in equilibrium was shown to increase compliance, beyond a given lower bound any further reduction in inspection of group 2 firms is not optimal as it is excessively costly to do so. Increasing the transition probability, on the other hand, was shown to increase compliance and so setting the transition probability to zero is also costly.

Furthermore, contrary to empirical evidence suggesting that maximum penalties be increased considerably (Ostrom, 1990), the theoretical results in this paper indicate that punishment should have an upper bound if it is to achieve the purpose for which it is intended. Results show that marginal punishment should not exceed the marginal gains, since this only serves to increase illegal effort, with a corresponding negative impact on the fish biomass. Le Gallic and Cox (2006), emphasizes that even corrective measures carry a cost and, thus, care must be taken to establish the benefit of respective corrective measures. This view is supported by existing theory in the literature (De Merode et al., 2007). IUU activities are found in this paper to place less value on the future of the fishery by using discount factor higher than that which will ensure sustainable harvest over time. Firms violating discount the future heavily, thereby eroding any investment in the fishery.

This paper argued that a plausible reason for illegal behaviour even among quota owners could be the lack of permanent ownership rights under the quota system. The lack of transferability rights under the quota system could be disincentive to preserve the stock, and not to discount the future heavily, particularly for retiring fishers or firms planning to leave the fishery. This argument is supported by views earlier expressed by Arnason (1990). In the case of ITQ, however, the greed factor identified in this paper could be a major reason for engaging in illegal activities that are likely to erode any future benefits that may accrue from increases in stock levels. The paper confirms earlier theoretical suggestions that economic incentives may be sound economic policies to discourage illegal fishing (Costello and Guinness, 2010). Such incentives may include increasing operational and capital costs, subsidy removal, increasing the cost of engaging in illegal activities through punishment, as well as increasing the risk of engaging in illegal fishing activities.

Previous studies show that enforcement is costly and deterrence model alone does not adequately explain violation tendencies (De Merode et al., 2007). This implies that other economic incentives are required to complement the role of punishment, cost, and risk, as measures to correct illegal operations in the fisheries. The literature suggests that a management tool that may lower firms' incentive to engage in illegal activities is the effective enforcement of domestic management regimes. Domestic management regimes that are well designed and effectively enforced to ensure higher incomes for fishers are identified as an effective policy to lower firms' incentive to engage in illegal fishing (Ostrom, 1990). It is also argued that domestic fisheries generating higher incomes have lower incentive to engage in IUU activities (Kuperan and Sutinen, 1998; Sutinen and Kuperan, 1999). This means that the effective enforcement of well-designed domestic management regimes, an important determinant of the income of domestic fishers, can lead to a significant reduction in IUU activities.

The application of game theoretic concepts to analyse illegal activities in fisheries, as shown in this paper, is innovative. It is a unique approach to understanding the complex interactions between management and firms in the fishery industry. The approach is simple but provides insightful results that can guide policy in the quest to address the IUU problem and to conserve and sustain fish stocks across time. Applying this method to find plausible solutions to management challenges in internationally shared fishery is an interesting extension we investigate in future work. In addition, the assumption that the probability of inspection is not affected by the incidence of violation is an equally interesting case we investigate in the future.

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Appendix A

A.1

The expected profit of a group 1 firm complying at all times, can be expressed as

$$\begin{aligned} E^{00}[\pi_{1c}] &= \pi_{1c} + \beta\pi_{1c} + \beta^2\pi_{1c} + \beta^3\pi_{1c} + \dots. \\ &= \pi_{1c} + \beta\left[\pi_{1c} + \beta\pi_{1c} + \beta^2\pi_{1c} + \dots\right] \\ &= \pi_{1c} + \sum_{t=1}^{\infty}\beta^t\pi_{1c}. \end{aligned}$$

By the stationarity and infinite time horizon assumption, the expected profit of a group 1 firm complying at all times, $E^{00}[\pi_{1c}]$, can be expressed

$$\begin{aligned} E^{00}[\pi_{1c}] &= \pi_{1c} + \beta\left[\pi_{1c} + \beta\pi_{1c} + \beta^2\pi_{1c} + \dots\right] \\ &= \pi_{1c} + \beta E^{00}[\pi_{1c}] \end{aligned}$$

For a *type* 2 firm complying all the time, let the expected profit be given as

$$\begin{aligned} E^{00}[\pi_{2c}] &= \pi_{2c} + \beta\left[\mu_2\eta\pi_{1c} + (1-\mu_2\eta)\pi_{2c}\right] + \beta^2\left[\mu_2\eta\pi_{1c} + (1-\mu_2\eta)\pi_{2c}\right] + \dots \\ &= \pi_{2c} + \sum_{t=1}^{\infty}\beta^t\left(\mu_2\eta\pi_{1c}\right) + \sum_{t=1}^{\infty}\beta^t\left(1-\mu_2\eta\right)\pi_{2c} \\ &= \pi_{2c} + \mu_2\eta\sum_{t=1}^{\infty}\beta^t\pi_{1c} + \left(1-\mu_2\eta\right)\sum_{t=1}^{\infty}\beta^t\pi_{2c} \end{aligned}$$

Then by the stationarity and infinite time horizon assumption, the expected profit of a group 2 firm complying at all times, $E^{00}[\pi_{2c}]$, can be expressed as

$$\begin{aligned} E^{00}[\pi_{2c}] &= \pi_{2c} + \mu_2\eta\beta\left[\sum_{t=0}^{\infty}\beta^t\pi_{1c}\right] + \left(1-\mu_2\eta\right)\beta\left[\sum_{t=0}^{\infty}\beta^t\pi_{2c}\right] \\ &= \pi_{2c} + \mu_2\eta\beta E^{00}[\pi_{2c}] + \left(1-\mu_2\eta\right)\beta E^{00}[\pi_{2c}] \end{aligned}$$

Analogically the cases of violation for group 1 and group 2 firms are derived and expressed in Table 4.

A.2

Solving the equations under Section **??**.

In order to obtain the expected profits of the four strategies each firm adopts, the equations in Table 4 are solved simultaneously in the following manner.

[1]. Solving for expected profits under strategy s_{00}, i.e. comply in both groups G_1 and G_2

Let $E^{^{00}}[\pi_{_{1c}}]: \quad E^{^{00}}[\pi_{_{1c}}] = \pi_c + \beta E^{^{00}}[\pi_{_{1c}}]$

This gives $E^{^{00}}[\pi_{_{1c}}](1-\beta) = \pi_c$,

yielding

$$E[\pi_{_{1c}}] = \frac{\pi_c}{1-\beta} \tag{14}$$

Next, letting, $E^{^{00}}[\pi_{_{2c}}]$: $\quad E[\pi_{_{2c}}] = \pi_c + \beta\mu_2\eta E[\pi_{_{1c}}] + \beta(1-\mu_2\eta)E[\pi_{_{2c}}]$,

yields

$$E[\pi_{_{2c}}][1-\beta(1-\mu_2\eta)] = \pi_c + \beta\mu_2\eta E[\pi_{_{1c}}]$$

Then substituting for $E[\pi_{_{1c}}]$ from (14)

we obtain

$$E[\pi_{_{2c}}]([1-\beta(1-\mu_2\eta)] = \pi_{2c} + \beta\mu_2\eta\left(\frac{\pi_c}{1-\beta}\right)$$

and

$$E[\pi_{_{2c}}] = \frac{(1-\beta)\pi_c + \beta\mu_2\eta\pi_c}{(1-\beta)(1-\beta(1-\mu_2\eta))}.$$

Rearranging the numerator of the above equation and canceling terms, the following result is obtained

$$E[\pi_{_{2c}}] = \frac{\pi_c}{1-\beta}. \tag{15}$$

[2]. Solving for expected profits under strategy s_{01}, i.e. comply in group G_1 and violate in G_2

Letting $E^{^{01}}[\pi_{_{1c}}]: \quad E[\pi_{_{1c}}] = \pi_c + \beta E[\pi_{_{1c}}]$

and re-arranging yields

$$E[\pi_{_{1c}}] = \frac{\pi_c}{1-\beta}. \tag{16}$$

From $E^{^{01}}[\pi_{_{2v}}]: \quad E[\pi_{_{2v}}] = \pi_{2v} - \mu_2 F + \beta E[\pi_{_{2v}}]$

we obtain

$$E[\pi_{_{2v}}] = \frac{\pi_{2v} - \mu_2 F}{1-\beta}. \tag{17}$$

[3]. Solving for expected profits under strategy s_{10}, i.e. a firm violating in group G_1

and complying in G_2, yield the following respective results for G_1 and G_2 firms

As before, we first let, $E^{10}[\pi_{1v}]: \quad E[\pi_{1v}] = \pi_{1v} - \mu_1 F + \mu_1\beta E[\pi_{2c}] + \beta(1-\mu_1)E[\pi_{1v}]$,

from which we obtain;

$$E[\pi_{1v}][1-\beta(1-\mu_1)] = \pi_{1v} - \mu_1 F + \mu_1\beta E[\pi_{2c}], \tag{18}$$

and therefore

$$E[\pi_{1v}] = \frac{\pi_{1v} - \mu_1 F + \mu_1\beta E[\pi_{2c}]}{[1-\beta(1-\mu_1)]}, \tag{19}$$

after the necessary re-arrangements.
Next, for $E^{10}[\pi_{2c}]: \quad E[\pi_{2c}] = \pi_c + \beta\mu_2\eta E[\pi_{1v}] + \beta(1-\mu_2\eta)E[\pi_{2c}]$
we obtain

$$E[\pi_{2c}][1-\beta(1-\mu_2\eta)] = \pi_c + \beta\mu_2\eta E[\pi_{1v}]$$

.

Then plugging in $E[\pi_{1v}]$ from (19) yields

$$E[\pi_{2c}][1-\beta(1-\mu_2\eta)] = \pi_c + \beta\mu_2\eta\left(\frac{\pi_{1v} - \mu_1 F + \mu_1\beta E[\pi_{2c}]}{[1-\beta(1-\mu_1)]}\right).$$

After the necessary expansion of the above equation the following is obtained

$$E[\pi_{2c}][1-\beta(1-\mu_2\eta)(1-\beta(1-\mu_1))] = \pi_c[1-\beta(1-\mu_1)] + \beta\mu_2\eta(\pi_{1v} - \mu_1 F) + \beta^2\mu_1\mu_2\eta E[\pi_{2c}]$$

and which results in

$$E[\pi_{2c}][(1-\beta(1-\mu_2\eta))(1-\beta(1-\mu_1)) - \beta^2\mu_1\mu_2\eta] = \pi_c[1-\beta(1-\mu_1)] + \beta\mu_2\eta(\pi_{1v} - \mu_1 F).$$

To obtain the required expression for $E[\pi_{2c}]$, expected profit when complying in group 2, we do the following. We let the L.H.S be defined as A and the R.H.S as B, such that $A = B$.
Then simplifying A

$$\begin{aligned}
A &\equiv E[\pi_{2c}][1-\beta(1-\mu_1) - \beta(1-\mu_2\eta) + \beta^2(1-\mu_1)(1-\mu_2\eta) - \beta^2\mu_1\mu_2\eta] \\
&= E[\pi_{2c}][1-\beta(1-\mu_1) - \beta(1-\mu_2\eta) + \beta^2(1-\mu_1-\mu_2\eta+\mu_1\mu_2\eta) - \beta^2\mu_1\mu_2\eta] \\
&= E[\pi_{2c}][1-\beta(1-\mu_1) - \beta(1-\mu_2\eta) + \beta^2(1-\mu_1-\mu_2\eta) + \beta\mu_1\mu_2\eta - \beta^2\mu_1\mu_2\eta] \\
&= E[\pi_{2c}][1-\beta(1-\mu_1) - \beta + \beta\mu_2\eta + (1-\mu_1) - \beta^2\mu_2\eta] \\
&= E[\pi_{2c}][1-\beta(1-\mu_1)(1-\beta) - \beta + \beta\mu_2\eta(1-\beta)] \\
&= E[\pi_{2c}](1-\beta)[1-\beta(1-\mu_1) + \beta\mu_2\eta] = E_{2c}(1-\beta)[1-\beta(1-\mu_1-\mu_2\eta)].
\end{aligned}$$

Then equating $A = B$, yields the following expression

$$E[\pi_{2c}](1-\beta)[1-\beta(1-\mu_1-\mu_2\eta)] = \pi_c[1-\beta(1-\mu_1)] + \beta\mu_2\eta(\pi_{1v}-\mu_1F)$$

which is re-arranged to give the following expression for $E[\pi_{2c}]$

$$E[\pi_{2c}] = \frac{\pi_c[1-\beta(1-\mu_1)] + \beta\mu_2\eta(\pi_{1v}-\mu_1F)}{(1-\beta)[1-\beta(1-\mu_1-\mu_2\eta)]}. \tag{20}$$

Then plugging (20) back into (19) above, results in

$$E[\pi_{1v}] = \frac{\pi_{1v} - \mu_1F + \mu_1\beta\left(\dfrac{\pi_c[1-\beta(1-\mu_1)] + \beta\mu_2\eta(\pi_{1v}-\mu_1F)}{(1-\beta)[1-\beta(1-\mu_1-\mu_2\eta)]}\right)}{[1-\beta(1-\mu_1)]}.$$

We then simplify the numerator of the above expression as follows.
We let

$$\Delta \equiv \frac{(\pi_{1v}-\mu_1F)(1-\beta)[1-\beta(1-\mu_1-\mu_2\eta)] + \beta\mu_1\pi_c[1-\beta(1-\mu_1)] + \beta^2\mu_1\mu_2\eta(\pi_{1v}-\mu_1F)}{(1-\beta)[1-\beta(1-\mu_1-\mu_2\eta)]}$$

$$= \frac{(\pi_{1v}-\mu_1F)(1-\beta)[1-\beta(1-\mu_1)] + (\pi_{1v}-\mu_1F)(1-\beta)\beta\mu_2\eta + \beta\mu_1\pi_c[1-\beta(1-\mu_1)] + \beta^2\mu_1\mu_2\eta(\pi_{1v}-\mu_1F)}{(1-\beta)[1-\beta(1-\mu_1-\mu_2\eta)]}$$

$$= \frac{[1-\beta(1-\mu_1)]\left((1-\beta)(\pi_{1v}-\mu_1F) + \beta\mu_2\eta(\pi_{1v}-\mu_1F) + \beta\mu_1\pi_c\right)}{(1-\beta)[1-\beta(1-\mu_1-\mu_2\eta)]}.$$

Next, is to put the numerator and denominator of $E[\pi_{1v}]$ together to obtain the following expression

$$E[\pi_{1v}] = \frac{\dfrac{[1-\beta(1-\mu_1)]\left((\pi_{1v}-\mu_1F)(1-\beta) + \beta\mu_2\eta(\pi_{1v}-\mu_1F) + \beta\mu_1\pi_{2c}\right)}{(1-\beta)[1-\beta(1-\mu_1-\mu_2\eta)]}}{[1-\beta(1-\mu_1)]}.$$

We then cancel out terms to obtain the desired expression in $E[\pi_{1v}]$ and $E[\pi_{2c}]$, as

$$E[\pi_{1v}] = \frac{\beta\mu_1\pi_c + (\pi_{1v}-\mu_1F)[1-\beta(1-\eta_2\eta)]}{(1-\beta)[1-\beta(1-\mu_1-\mu_2\eta)]} \tag{21}$$

and;

$$E[\pi_{2c}] = \frac{\pi_c[1-\beta(1-\mu_1)] + \beta\mu_2\eta(\pi_{1v}-\mu_1F)}{(1-\beta)[1-\beta(1-\mu_1-\mu_2\eta)]} \tag{22}$$

[4]. Solving for expected profits under strategy s_{11}, that is, violating in both states

G_1 and G_2
As before, we let $E^{11}[\pi_{1_v}]: \quad E[\pi_{1_v}] = \pi_{1v} - \mu_1 F + \mu_1 \beta E_{2v} + \beta(1-\mu_1)E[\pi_{1_v}]$.
We then re-arrange the above to obtain equation (23), as

$$E[\pi_{1_v}] = \frac{\pi_{1v} - \mu_1 F + \mu_1 \beta E[\pi_{2_v}]}{[1-\beta(1-\mu_1)]} \tag{23}$$

Similarly, letting, $E^{11}[\pi_{2_v}]: \quad E[\pi_{2_v}] = \pi_{2v} - \mu_2 F + \beta E[\pi_{2_v}]$, and re-arranging yields

$$E[\pi_{2_v}] = \frac{\pi_{2v} - \mu_2 F}{1-\beta}. \tag{24}$$

To obtain the desired expression in $E[\pi_{1_v}]$, we substitute (24) back into (23) above and re-arrange to get equation (25) as follows

$$E[\pi_{1_v}] = \frac{\pi_{2v} - \mu_1 F + \beta\left(\dfrac{\pi_{2v} - \mu_2 F}{1-\beta}\right)}{[1-\beta(1-\mu_1)]} = \frac{(1-\beta)[\pi_{1v} - \mu_1 F] + \mu_1\beta(\pi_{2v} - \mu_2 F)}{(1-\beta)[1-\beta(1-\mu_1)]}$$

and hence

$$E[\pi_{1_v}] = \frac{(1-\beta)[\pi_{1v} - \mu_1 F] + \mu_1\beta(\pi_{2v} - \mu_2 F)}{(1-\beta)[1-\beta(1-\mu_1)]} \tag{25}$$

Thus, solving for expected profits under strategy s_{11}, that is, violating in both groups G_1 and G_2, produce the following results for groups 1 and 2 firms violating as

$$E[\pi_{1_v}] = \frac{(1-\beta)[\pi_{1v} - \mu_1 F] + \mu_1\beta(\pi_{2v} - \mu_2 F)}{(1-\beta)[1-\beta(1-\mu_1)]} \tag{26}$$

and

$$E[\pi_{2_v}] = \frac{\pi_{2v} - \mu_2 F}{1-\beta}. \tag{27}$$

Proof of Lemmas
Lemma 1
1. Starting with the condition $\pi_c > \pi_{2v} - \mu_2 F$
From Equations (14 and 17), $\dfrac{\pi_c}{1-\beta} = \dfrac{\pi_{2v} - \mu_2 F}{1-\beta}$ iff $\pi_c = \pi_{2v} - \mu_2 F \ \forall\ \beta \neq 1$. But the condition $\pi_c > \pi_{2v} - \mu_2 F \implies \dfrac{\pi_c}{1-\beta} > \dfrac{\pi_{2v} - \mu_2 F}{1-\beta}, \forall\ \beta \neq 1$. This implies $S_{00} > S_{01}$, from the profit maximizing assumption.
2. Condition $\pi_c < \pi_{2v} - \mu_2 F$
From Equation (25), $\dfrac{(1-\beta)[\pi_{1v} - \mu_1 F] + \mu_1\beta(\pi_{2v} - \mu_2 F)}{(1-\beta)[1-\beta(1-\mu_1)]} > \dfrac{(1-\beta)[\pi_{1v} - \mu_1 F] + \mu_1\beta\pi_c}{(1-\beta)[1-\beta(1-\mu_1)]}$, iff $\pi_{2v} - \mu_2 F > \pi_c$. Rearranging this relation yields

$$\frac{\pi_{2v} - \mu_2 F}{1-\beta} > \frac{\pi_c}{1-\beta}, \qquad \forall\ \beta \neq 1.$$

,
Again, from the profit maximizing assumption this implies $S_{11} > S_{01}$. Hence (1) and (2) satisfy Lemma 1. □

Lemma 2

From Equation (20) when $\pi_c = \pi_{1v} - \mu_1 F$ the following is observed: $\frac{\pi_c[1-\beta(1-\mu_1)] + \beta\mu_2\eta(\pi_{1v} - \mu_1 F)}{(1-\beta)[1-\beta(1-\mu_1-\mu_2\eta)]} = \frac{\pi_c[1-\beta(1-\mu_1-\mu_2\eta)]}{(1-\beta)[1-\beta(1-\mu_1-\mu_2\eta)]}$, yielding $\frac{\pi_c}{1-\beta} \equiv E^{00}$. Equation (14) implies $E^{00} \equiv \frac{\pi_c}{1-\beta}$, giving $E^{00} = E^{10}$. Equation (27) implies $E^{11} \equiv \frac{\pi_{2v} - \mu_2 F}{1-\beta}$. But the condition $\pi_c > \pi_{2v} - \mu_2 F$ shows that $\frac{\pi_c}{1-\beta} > \frac{\pi_{2v} - \mu_2 F}{1-\beta}\ \forall\ \beta \neq 1$. Hence $E^{00} = E^{10} > E^{11}$, and therefore $S_{00} = S_{10} > S_{11}$. From the profit maximizing assumption $S_{00} = S_{10}$ satisfies Lemma 2. □

A.3

Solving the optimization problem with respect to μ_1, μ_2, F, η, γ, and φ. We first let the leverage, L, be expressed as

$$L = \frac{\mu_1\mu_2(1+\eta)}{\mu_1+\mu_2\eta} + \gamma\left[\pi_{2v} - \mu_2 F + \frac{\beta\mu_2\eta[\pi_{2v} - \pi_{1v} + \mu_1 F - \mu_2 F]}{1-\beta(1-\mu_1)} - \pi_c\right] + \varphi\left[\Omega - \frac{\mu_1}{\mu_1+\mu_2\eta}\right]$$

We then take the first order condition (FOC) with respect to each of the parameters above.

Starting with μ_1.

Let

$$\frac{\partial L}{\partial \mu_1} = \frac{\mu_2(1+\eta)(\mu_1+\mu_2\eta)}{(\mu_1+\mu_2\eta)^2} + \frac{\gamma\beta\mu_2\eta F[1-\beta(1-\mu_1)] - \gamma\mu_1\mu_2\beta^2\eta F}{[1-\beta(1-\mu_1)]^2} = 0.$$

Re-arranging the above, we solve for φ as follows:

$$\frac{\mu_2(1+\eta)[\mu_1+\mu_2\eta-\mu_1]}{(\mu_1+\mu_2\eta)^2} - \frac{\varphi[\mu_1+\mu_2\eta-\mu_1]}{(\mu_1+\mu_2\eta)^2} + \frac{\gamma\beta\mu_2\eta F[1-\beta(1-\mu_1)-\mu_1\beta]}{[1-\beta(1-\mu_1)]^2} = 0$$

giving

$$\frac{\mu_2(1+\eta)-\varphi}{(\mu_1+\mu_2\eta)^2} + \frac{\gamma\beta F(1-\beta)}{[1-\beta(1-\mu_1)]^2} = 0$$

and therefore

$$\varphi = \mu_2 (1+\eta) + \frac{\gamma\beta F (1-\beta)(\mu_1+\mu_2\eta)^2}{[1-\beta(1-\mu_1)]^2}. \tag{28}$$

Next, is the FOC with respect to μ_2.

Let

$$\frac{\partial L}{\partial \mu_2} = \frac{\mu_1 (1+\eta)(\mu_1+\mu_2\eta) - \mu_1\mu_2 (1+\eta)\eta}{(\mu_1+\mu_2\eta)^2} - \gamma F - \frac{2\gamma\beta\mu_2\eta F [1-\beta(1-\mu_1)]}{[1-\beta(1-\mu_1)]^2} - \left[-\frac{\varphi\mu_1\eta}{(\mu_1+\mu_2\eta)^2}\right] = 0.$$

Re-arranging the above we obtain the expression in (29) as:

$$\frac{\mu_1 (1+\eta)[\mu_1+\mu_2\eta-\mu_2\eta] + \varphi\mu_1\eta}{(\mu_1+\mu_2\eta)^2} - \gamma F - \frac{2\gamma\beta\mu_2\eta F}{1-\beta(1-\mu_1)} = 0$$

and therefore

$$\frac{\mu_1[\mu_1(1+\eta)+\varphi\eta]}{(\mu_1+\mu_2\eta)^2} = \frac{\gamma F [1-\beta(1-\mu_1)+2\beta\mu_2\eta]}{1-\beta(1-\mu_1)}. \tag{29}$$

Next, is the FOC with respect to F.

Let

$$\frac{\partial L}{\partial F} = -\gamma\mu_2 + \frac{\gamma\beta\mu_2\eta(\mu_2-\mu_1)[1-\beta(1-\mu_1)]}{[1-\beta(1-\mu_1)]^2} = 0.$$

By re-arrangement, we solve for μ_1 as follows

Let

$$\frac{\gamma\beta\mu_2\eta(\mu_2-\mu_1) - \gamma\mu_2[1-\beta(1-\mu_1)]}{1-\beta(1-\mu_1)} = 0$$

and;

$$\mu_1\beta(\eta-1) = \beta(\eta\mu_2-1)+1$$

Thus, obtaining μ_1 as

$$\mu_1 = \frac{\beta(\eta\mu_2-1)+1}{\beta(\eta-1)} \tag{30}$$

The FOC with respect to η is next.

Let

$$\frac{\partial L}{\partial \eta} = \frac{\mu_1\mu_2(\mu_1+\mu_2\eta) - \mu_1\mu_2(1+\eta)\mu_2}{(\mu_1+\mu_2\eta)^2} + \frac{\gamma\beta\mu_2[\pi_2-\pi_1+\mu_1 F-\mu_2 F]}{1-\beta(1-\mu_1)} - \left[-\frac{\varphi\mu_1\mu_2}{(\mu_1+\mu_2\eta)^2}\right] = 0$$

$$= \frac{\mu_1\mu_2(\mu_1+\mu_2\eta) - \mu_1\mu_2(1+\eta)\mu_2 + \varphi\mu_1\mu_2}{(\mu_1+\mu_2\eta)^2} + \frac{\gamma\beta\mu_2[\pi_2-\pi_1+\mu_1 F-\mu_2 F]}{1-\beta(1-\mu_1)} = 0.$$

We re-organise the above to obtain the expression (31) below.

$$\frac{\mu_1\left(\mu_1-\mu_2+\varphi\right)}{\left(\mu_1+\mu_2\eta\right)^2}=-\frac{\gamma\beta\mu_2[\pi_2-\pi_1+\mu_1F-\mu_2F]}{1-\beta(1-\mu_1)} \tag{31}$$

Next, is the FOC with respect to γ

Let

$$\frac{\partial L}{\partial\gamma}=\pi_2-\mu_2F+\frac{\beta\mu_2\eta[\pi_2-\pi_1+\mu_1F-\mu_2F]}{1-\beta(1-\mu_1)}-\pi_c=0$$

Similarly, after the necessary re-arrangements, we solve for π_c as

$$\pi_c=\pi_2-\mu_2F+\frac{\beta\mu_2\eta[\pi_2-\pi_1+\mu_1F-\mu_2F]}{1-\beta(1-\mu_1)}. \tag{32}$$

Finally, we do the same with respect to φ, and solve for Ω as follows

$$\frac{\partial L}{\partial\varphi}=\Omega-\frac{\mu_1}{\mu_1+\mu_2\eta}=0$$

which yields

$$\Omega=\frac{\mu_1}{\mu_1+\mu_2\eta}. \tag{33}$$

Appendix B

The objective here is to solve for marginal revenue (MR) and marginal cost (MC), given legal (E^L) and illegal (E^{IL}) efforts, using the revenue and cost functions.

$$TR_{10} = \frac{pqK}{A}\left[(\beta+Q)\left(E^L - \frac{q}{r}[E^{2L} + E^{IL}E^L]\right) + Q\left(E^{IL} - \frac{q}{r}[E^L E^{IL} + E^{2IL}]\right)\right]$$

$$TC_{10} = \frac{1}{A}\left[c\left((\beta+Q)E^L + QE^{IL}\right) + Q\mu_1 fqK\left(E^{IL} - \frac{q}{r}[E^L E^{IL} + E^{2IL}]\right)\right]$$

After the necessary expansion of both equations, the following first order conditions are determined

1. We first take the FOC with respect to E^L, giving us the MR and MC with respect to E^L as, respectively

$$\frac{\partial TR_{10}}{\partial E^L} = \frac{pqK}{A}\left[(\beta+Q)\left(1 - \frac{q}{r}[2E^L + E^{IL}]\right) - \frac{q}{r}QE^{IL}\right]$$

and

$$\frac{\partial TC_{10}}{\partial E^L} = \frac{1}{A}\left[c(\beta+Q) - \frac{q^2}{r}Q\mu_1 fKE^{IL}\right].$$

For maximum economic yield (MEY), given (E^L, E^{IL}), implies that $\frac{\partial TR_{10}}{\partial E^L} = \frac{\partial TC_{10}}{\partial E^L}$, which is equivalent to $MR_{E^L} = MC_{E^L}$.

Recall that $A = (1-\beta)[1-\beta(1-\mu_1-\mu_2\eta)]$, and $Q = [1-\beta(1-\mu_1\eta)]$

Thus after equating and re-arranging the above FOCs, the MEY legal effort level chosen by firms when violating under strategy s_{10} is given as

$$E^L_{MEY/10} = \frac{r}{2q}\left(1 - \frac{c}{pqK}\right) - \frac{1}{2p}\left[p + \frac{Q(p-\mu_1 f)}{(\beta+Q)}\right]E^{IL}_{MEY/10}.$$

2. As before we find MR and MC with respect to E^{IL}, as follows

Let;

$$\frac{\partial TR_{10}}{\partial E^{IL}} = \frac{pqK}{A}\left[Q(1 - 2\frac{q}{r}E^{IL}) - \frac{q}{r}(\beta+2Q)\right]$$

and

$$\frac{\partial TC_{10}}{\partial E^{IL}} = \frac{Q}{A}\left[c + \mu_1 f q K \left(1 - \frac{q}{r}[E^{L} + 2E^{IL}]\right)\right].$$

Again, for maximum economic yield (MEY), given (E^{L}, E^{IL}), implies that $\frac{\partial TR_{10}}{\partial E^{IL}} = \frac{\partial TC_{10}}{\partial E^{IL}}$, which is equivalent to $MR_{E^{IL}} = MC_{E^{IL}}$
This relation gives the following MEY illegal effort level chosen by firms when violating under strategy S_{10}

$$E^{IL}_{MEY/10} = \frac{r}{2q}\left(1 - \frac{c}{qK(p - \mu_1 f)}\right) - \frac{1}{2}\left[1 + \frac{(\beta + Q)p}{Q(p - \mu_1 f)}\right] E^{L}_{MEY/10}.$$

Appendix C

Proof 1.

No illegal fishing benchmark.

Let the Hamiltonian be expressed as

$$\mathcal{H} = e^{-\delta t}\left\{(pqB_t - c)E_t + \lambda_t\left[rB_t\left(1 - \frac{B_t}{K}\right) - qB_tE_t\right]\right\}$$

and the necessary condition with respect to effort, E_t, be given as

$$(pq_{B_t} - c) - \lambda_t qB_t = 0$$

Then re-arranging and solving for λ_t, gives

$$\lambda_t = \frac{pqB_t - c}{qB_t}.$$

which can also be written in the form:

$$\lambda_t = p - \frac{c}{qB_t}.$$

The necessary condition with respect to biomass, B_t, yields

$$pqE_t + \lambda_t r\left(1 - \frac{2B_t}{K}\right) - \lambda_t qE_t = -\dot{\lambda}_t + \delta\lambda_t \tag{34}$$

Finally the necessary condition with respect to λ_t, results in

$$E_t = \frac{r}{q}\left(1 - \frac{B_t}{K}\right)$$

Sustainable steady-state requires that $F(B,\ E) = qB^\star E^\star$, and $\dot{B}_t = 0 = \dot{\lambda}_t$
This implies

$$E^\star = \frac{r}{q}\left(1 - \frac{B^\star}{K}\right).$$

And from the steady-state conditions, Equation (21) becomes

$$\delta\lambda^\star = pqE^\star + \lambda^\star r\left(1-\frac{2B^\star}{K}\right) - \lambda^\star qE^\star$$

and

$$\lambda^\star = \frac{pqB^\star - c}{qB^\star} = p - \frac{c}{qB^\star}.$$

Then substituting for $\lambda^\star$ and solving for δ as follows gives the modified golden rule Let

$$\delta\frac{pqB^\star - c}{qB^\star} = pq\left[\frac{r}{q}\left(1-\frac{B^\star}{K}\right)\right] + \left(p - \frac{c}{qB^\star}\right)\left[r\left(1-\frac{2B^\star}{K}\right) - q.\frac{r}{q}\left(1-\frac{B^\star}{K}\right)\right]$$

After the necessary re-arrangements we get

$$\delta\frac{pqB^\star - c}{qB^\star} = \frac{pqB^\star - c}{qB^\star}.r\left(1-\frac{2B^\star}{K}\right) + \frac{c}{qB^\star}.r\left(1-\frac{B^\star}{K}\right)$$

which finally gives the required expression for δ as

$$\delta = r\left(1-\frac{2B^\star}{K}\right) + r\left(1-\frac{B^\star}{K}\right)\frac{c}{pqB^\star - c}. \square$$

Proof 2
The case of IUU
From the assumption that firms conducting illegal activities employ illegal effort in addition to legal effort, we express the Hamiltonian as

$$\mathcal{H} = e^{-\delta t}\left\{(pqB_t - c)e_{it}^T - \mu_1 fqB_t(e_t^T - e_t^L) + \lambda_t\left[rB_t\left(1-\frac{B_t}{K}\right) - qB_te_{it}^T - (n-1)qB_te_{jt}^T\right]\right\}.$$

Recall that $e_{it}^T = e_{it}^L + e_{it}^{IL}$, which is equivalent to saying $e_{it}^{IL} = e_{it}^T - e_{it}^L$.
Then the necessary condition with respect to total effort of firm i at time t, e_{it}^T, after re-arrangements, yields the following expression in λ_t

$$\lambda_t = \frac{qB_t(p-\mu_1 f) - c}{qB_t}.$$

Then the necessary with respect to biomass, B_t, results in

$$pqe_{it}^T - \mu_1 fq(e_t^T - e_t^L) + \lambda_t \left\{ r\left(1 - \frac{2B_t}{K}\right) - qe_{it}^T - (n-1)qe_{jt}^T \right\} = -\dot{\lambda}_t + \delta\lambda_t.$$

We assume symmetry about illegal effort choice, that is, all firms employing illegal effort are identical, thus $e_{it} = e_{jt} \equiv e_{it}$. Therefore, the necessary condition with respect to λ_t gives, yields

$$e_{it}^T = \frac{r}{nq}\left(1 - \frac{B_t}{K}\right).$$

This gives the effort level at any time, t. Using the same symmetric assumption as above, let the steady-state effort be expressed as

$$\overline{e}^T = \frac{r}{nq}\left(1 - \frac{\overline{B}}{K}\right).$$

Hence in steady-state we obtain the following the expression

$$pq\overline{e}^T - \mu_1 fq(\overline{e}^T - \overline{e}^L) + \bar{\lambda} \left\{ r\left(1 - \frac{2\overline{B}}{K}\right) - q\overline{e}^T - (n-1)q\overline{e}^T \right\} = \delta\bar{\lambda}.$$

After the necessary algebraic re-arrangements, and solving for δ, we obtain the required MGR as

$$\delta = r\left(1 - \frac{2\overline{B}}{K}\right) - \frac{r}{n}\left(1 - \frac{\overline{B}}{K}\right)\frac{q(n-1)(p-\mu_1 f)\overline{B} - nc}{q\overline{B}(p-\mu_1 f) - c} + \frac{q^2\overline{B}\mu_1 f e^{IL}}{q\overline{B}(p-\mu_1 f) - c}. \quad \square$$