Discussion paper

A Corporate-Crime Perspective on Fisheries: Liability Rules and Non-Compliance

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A Corporate-Crime Perspective on Fisheries: Liability Rules and Non-Compliance

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Abstract: The existing fisheries economics literature analyzes compliance problems by treating the fishing firm as one cohesive unit, but in many cases, violations are committed by agents acting on behalf of a firm. To account for this, we analyze the principal-agent relationship within the fishing firm. In the case where the firm directly benefits from illegal fishing, the firm must induce its crew to violate regulations through the incentive scheme. Within this framework, we analyze how the allocation of liability between fishing firms and crew affects quota violations and the ability to design a socially efficient fisheries policy. We show that without wage frictions, it does not matter whom is held liable. However, under the commonly used share systems of remuneration, crew liability generally yields a more efficient outcome than firm liability. Furthermore, asset restrictions may affect the outcome under various liability rules.

1. Introduction

Unreported landings and other violations of fisheries regulations represent a challenge in most commercial fisheries. Due to the common-property nature of fisheries, over-fishing and rent dissipation are serious problems. To avoid rent dissipation, managers typically impose regulations to restrict fishing effort and harvest levels. However, this does not remove the individual firm's incentives to harvest in excess of socially optimal levels, and hence, the fishing firm may have incentives to violate the regulations.

In this paper, we ask how the allocation of liability for regulatory violations, between the fishing firm (or the owner) and its employees, affects the level of compliance. While the firm owns any landed fish and thus benefits directly from, for example, quota violations, the payoff for the employees, who make the actual harvesting decision, primarily depend on the compensation scheme offered by the firm. To analyze the implications of this potential conflict of interest for regulatory compliance, we use principal-agent theory to investigate the relationship between the firm and the employees in the context of a vessel that can (illegally) exceed its fishing quota. We then integrate this into the economic model of crime. This extends the existing literature on fisheries law enforcement as it broadens the understanding of illegal behavior and the role of liability rules. Such knowledge is valuable also from a policy perspective, as it might enable regulators to increase the deterrence effect of the enforcement system without spending more resources.

Our analysis shows that when the firm has full flexibility in designing wage contracts the allocation of liability between firm and crew does not matter. Furthermore, we show that if we introduce wage frictions, so that firms no longer have full flexibility in designing wage contracts, the allocation of liability might matter. To investigate this in the context of fisheries, we study two specifications of the commonly used share-system of remuneration: profit sharing and revenue sharing. With such sharing rules, the firm must pay the crew a share of the vessel's

profits or revenues, which dramatically reduces the flexibility of the firm in designing incentives schemes. Consequently, the firm can no longer induce the employee to harvest any desired quantity, and consequently, it matters whether one holds the firm or the crew liable for violations. We also show how wage frictions in the form of limited assets for either the firm or the employee may prevent the possibility of designing an efficient enforcement policy.

The result that liability does not matter in the absence of wage (or other) frictions, is in line with the environmental economics literature on liability. However, while this literature typically assumes a static flow externality, where pollution (flow) is an undesirable output (Sappington, 1983; Segerson and Tietenberg, 1992; Bontems *et al.*, 2004; de Vries and Franckx, 2012), we consider a dynamic stock externality. The dynamic stock externality arises within our framework because neither the firm nor the employees take into account how their harvest decisions affect the future availability of fish (the resource restriction). With a dynamic stock externality, the marginal cost of illegal harvesting, and thus the optimal enforcement, depends on the current status of the stock and will therefore change over time until a steady state is reached. In contrast, the existing literature on liability generally considers static policies.

Our framework uses the economic model of crime by Becker (1968), which has formed the basis for much of the previous work on noncompliance both in the fisheries economics literature and beyond. The fishing firm violates fishing regulations if the expected gains exceed the expected punishment (Sutinen and Anderson, 1985; Furlong, 1991; Hatcher, 2009; Arnason, 2013). In this previous work, one can align the incentives of risk neutral fishing firms with those of a social planner by setting the expected penalty equal to the external cost of illegal landings (Anderson and Lee, 1986; Coelho, 2012; Arnason, 2013). The fisheries economic literature presents many extensions of this basic enforcement model but all previous studies have in common that they treat the fishing firm as an individual decision maker. Consequently,

they disregard any principal-agent problems between the firm and the employees, and what happens within the firm is not part of the analysis.[1] Hence, our analysis extends this work by also investigating what happens *within* the firm.

A large literature analyzes corporate crime within a principal-agent framework (Mullin and Snyder, 2005; Mullin and Snyder, 2010). The majority of this literature studies the case when the employee acts in his own best interest when committing a corporate crime. However, in the case of the fishery, the opposite situation seems more plausible. The fishing firm owns any fish caught and therefore obtains direct benefits from quota violations. The benefits of the crew, in contrast, mainly rely on the compensation or salary scheme offered by the firm.[2] Few studies analyze this setup, but exceptions include the work by Mullin and Snyder (2005) and (2010). They develop a corporate-crime model in which the firm benefits from violations carried out by the employees, while the employees obtain no direct benefit from the corporate crime. Within this model, they analyze optimal sanctioning and investigate under what circumstances a regulator should punish employees, the firm, or both parties for corporate crimes. They focus particularly on the role of indemnification clauses in the contract between the firm and the employee and ask whether one should ban such clauses. In this paper, we show that indemnification clauses for employees generally are efficient in fisheries. However, if the firm faces a binding asset constraint, indemnification clauses have no effect.

There are many examples of employees making decisions on behalf of a firm, including decisions to violate regulations (Kornhauser, 1982; Arlen, 2013). In terms of fisheries, this is perhaps particularly relevant in large-scale fisheries, where firms own vessels and often employ

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[1] Nøstbakken (2008) contains an overview of the fisheries economic literature on law enforcement.

[2] We disregard the possibility that employees fish illegally using the firm's equipment and sell these illegal catches themselves.

a large crew of professional fishermen. In many cases, the owners of the fishing firms do not work onboard the vessels, but function as managers from shore or investors. In our analysis, we assume perfect information between the firm, on the one hand, and the skipper and crew on the other. One might argue that if mangers act from the shore, there might be asymmetric information and strategic behavior between the principal and the agent. However, in this context, we believe the assumptions of full information and absence of strategic behavior are justified since they allow us to focus more closely on the effects of the liability allocation between the firm and the crew. This is also a common approach in the general economic liability literature (Segerson and Tietenberg, 1992; de Vries and Franckx, 2012).

Our study also relates to the work on remuneration systems in fisheries (Bergland, 1995; Matthiasson, 1999; Nguyen and Leung, 2009; Thuy et al., 2013). This work primarily focuses on how a fishing firm should specify the share system so that the crew acts in the firm's best interest. A commonly used argument in the literature is that firms use inputs most efficiently if the cost and revenue shares are equal. Bergland (1995) and Thuy et al. (2013) show that this only holds if agents are risk-neutral and if the relative size of the share parameters does not influence willingness of the employees to supply effort. Matthiasson (1999), and Nguyen and Leung (2009) analyze the case when employees face agent specific costs and conclude that the firm prefers a remuneration contract with a positive revenue share and a zero cost share. While we analyze the share system of remuneration, our focus is on which liability rules maximizes the value of the fishery given specific remuneration schemes. Nonetheless, in line with this literature, we find that profit sharing more often than revenue sharing can yield an efficient outcome, since it forces employees to at least take some of the costs of the firm into account when making (corporate) harvesting decisions.

A related strand of the literature considers optimal regulation of fisheries under asymmetric information about various parts of the fisheries system (Jensen and Vestergaard, 2002a, 2002b,

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2007; Hansen *et al.*, 2006; Aanesen and Armstrong, 2013).[3] Jensen and Vestergaard (2002a) assume asymmetric information about individual catches due to illegal landings and discards, and show how a stock tax can secure a first-best optimum when stock size is perfectly observable. Jensen and Vestergaard (2007) extend this analysis and show that with stock uncertainty, the stock tax must be combined with a tax on self-reported harvest. As an alternative to the stock-based tax, Hansen *et al.* (2006) suggest a tax on aggregated harvest. A more direct application of principal-agent theory is Jensen and Vestergaard (2002b), who assume asymmetric information about an exogenous cost parameter (adverse selection). They consider a state-owner fishery and show that a subsidy on fishing effort can secure a second-best optimum. Aanesen and Armstrong (2013) also consider asymmetric information about a cost parameter, with effort as a regulatory variable. Their focus is on the influence of environmental groups in fisheries, and show that effort taxation can secure a second-best optimum. All of the above papers consider regulation under asymmetric information and therefore focus on the principal-agent relation between a social planner and the fishermen. In this paper, we focus on optimal liability, and hence, the principal-agent relationship between the employees and the firm. The social planner now influence the decisions of both the employees and the firm through liability rules. Hence, we contribute to this literature by primarily focusing on liability rules rather than optimal regulations.

The organization of the paper is as follows. In the next section, we develop and analyze the base model. Section 3 contains an extension of this model by introducing wage frictions and relaxing the assumption about firms and employees having unlimited financial assets, while the final section offers some concluding remarks.

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[3] An overview of the literature on optimal regulation of fisheries under asymmetric information is given by Vestergaard (2010).

2. The Model and the Basic Result

We start out by developing the basic model. A fishery manager (social planner) determines an individual quota for each vessel at each instant of time, t, along with an enforcement policy. The fishery manager enforces quotas by inspecting random vessels. We assume that each fishing firm owns only one vessel. If a vessel exceeds the quota, it faces a given fine provided the manager detects the violation. The fine is costless and can be imposed either on the firm (the principal), the employees (the agent), or shared between the two. We assume perfect information between principal and agent to keep the analysis of liability rules tractable. Finally, we adopt a single-species assumption, and thus, disregard by-catches. However, it is straightforward to extend our model to account for multiple species.

Note that while we model an output regulated fishery in the following, it would be straightforward to modify our model to the case of input regulations. To see this, note that a dual formulation of a maximization problem can be transformed into a primal formulation of the problem (inputs) by using a standard, neoclassical production function with fishing effort and stock size as arguments (Neher, 1990). Hence, we can discuss input regulations based on the primal formulation of the problem, and, due to the relationship between the primal formulation and the dual formulation of the problem, the basic results in this paper generalize to the case of input regulations. This is particularly relevant for fisheries management in developing countries, which commonly rely on input regulations as the main management instrument, although individual quotas are gaining ground also in developing world fisheries (Jardine and Sanchirico, 2012).

We start out by analyzing the decentralized (private) outcome. Next, we compare this to the optimal harvesting policy found by solving a social planner's problem. In the decentralized case, firms design compensation schemes to maximize profits net of fine payments given the

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quotas, stock level, and enforcement policy, while employees decide how much to harvest given the compensation scheme and other relevant factors. The social planner, on the other hand, chooses the quota policy and the enforcement effort to maximize total rent from the fishery, where the enforcement effort, in turn, determines the detection rate for over-quota harvests. Note, however, that the firm and the fishermen take the detection rate as given.

2.1 Private outcome

We let h_{Lt} denote legal landings at time t, while h_{It} denotes illegal landings. The employees determine the total harvest level, h_{Lt} and h_{It}, given the wage contract offered by the firm. With full flexibility in designing the wage scheme, the firm can make the wage scheme contingent on both legal and illegal landings, implying a wage scheme: $W(h_{Lt}, h_{It})$. We assume that the employees and the firm each bear a share of the total harvest costs, which is given by $c(h_{Lt}, h_{It}, x_t)$. Given this, we can express the cost of the employees as $\alpha c(h_{Lt}, h_{It}, x_t)$, where $0 \le \alpha \le 1$ is the employee's exogenous cost share. [4] The harvest cost function has the following

properties: $\frac{\partial c}{\partial h_{Lt}} > 0$, $\frac{\partial^2 c}{\partial h_{Lt}^2} > 0$, $\frac{\partial c}{\partial h_{It}} > 0$, $\frac{\partial^2 c}{\partial h_{It}^2} > 0$, $\frac{\partial^2 c}{\partial h_{Lt} \partial h_{It}} > 0$, $\frac{\partial c}{\partial x_t} < 0$, $\frac{\partial^2 c}{\partial h_{It} \partial x_t} < 0$ and

$\frac{\partial^2 c}{\partial h_{Lt} \partial x_t} < 0$. These properties ensure that the problem is well behaved, and they will later help

us characterize the properties of the enforcement cost function. The assumptions reflect that it

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[4] Alternatively, we can assume separate cost functions for firm and employees, but this will not affect our main results. With a fully flexible wage function, the separate cost function for the employee will enter the firm's participation restriction (equation (3)) and thereby the firm's objective function (equation (4)). Thus, the results presented in the following are not affected by the assumption about the cost functions. When we analyze the share system of remuneration in section 3.1, we show that the employee is the real decision maker, and hence, the assumption about the cost function does not affect the results in this case either.

is costly for the employees to work onboard the vessel, and higher landings and lower stock sizes require that employees exert more effort.

When a vessel exceeds the quota, it risks being penalized. Depending on the liability rule, either the firm, the employee or both may then face a fine. Let $G(h_{It}) \geq 0$ and $F(h_{It}) \geq 0$ denote employee's and the firm's fines, respectively. Both penalty functions are zero in absence of illegal landings ($F(0) = 0$ and $G(0) = 0$), and increases exponentially with the level of illegal landings. In the base model, we assume that any value of $G(h_{It})$ and $F(h_{It})$ can be paid by the employee and the firm, respectively. The probability of detecting violators, $\gamma(e_t) > 0,$ is a function of enforcement effort, e_t, exerted by the regulator, but the probability is taken as given by the industry. Therefore, an employee's expected punishment if the vessel violates the quota is $\gamma G(h_{It})$. In the following, we analyze the behavior of a representative vessel (firm and employees). We start out by looking at the behavior of employees.

The expected payoff of a risk-neutral employee is:

$$W(h_{Lt}, h_{It}) - \alpha c(h_{Lt}, h_{It}, x_t) - \gamma G(h_{It}) \tag{1}$$

Hence, the employee earns a wage, but incurs a share of the harvesting cost and must pay the expected penalty for harvesting in excess of the quota.

The firm knows the expected payoff function of the employees and can observe both legal and illegal harvest. Thus, under standard assumptions about the properties of the cost function, and a flexible wage function, the fishing firm can use the compensation scheme to induce the employees to land any given quantity (Laffont and Tirole, 1993). In the base model, we impose no restrictions on the wage function, and hence, the principal can indirectly determine landings through the choice of the wage function. This makes the principal the real decision maker and therefore we turn to the optimization problem of the firm.

We assume that firms (and employees) are myopic, and do not consider the implications of their harvest decisions on the evolution of the stock. This is reasonable in a common property resource setting with many resource users, which implies that each user has only a negligible impact on the stock, and is a standard assumption in common property resource models (Clark, 1990; Neher, 1990). Given this, the firm maximizes profits with the parameters of the wage function as control variables. However, since the firm can indirectly determine both legal and illegal landings, we can simply use these landings directly as control variables instead of the wage function. Given that the firm faces the same probability of detection as the employees, the firm's expected penalty is $\gamma F(h_{It})$. On this basis, we can express the maximization problem of the risk-neutral firm as:

$$\max_{h_{Lt}, h_{It}} \left(p(h_{Lt} + h_{It}) - (1-\alpha)c(h_{Lt}, h_{It}, x_t) - W(h_{Lt}, h_{It}) - \gamma F(h_{It}) \right) \tag{2}$$

Subject to

$$h_{Lt} \leq Q_t \tag{3}$$

$$W(h_{Lt}, h_{It}) - \alpha c(h_{Lt}, h_{It}, x_t) - \gamma G(h_{It}) \geq U^0 \tag{4}$$

where p is the output price,[5] Q_t is the individual quota, and U^0 is the reservation payoff of the crew.

Note from the objective function (2) that the firm, just like the employees, only incurs a fraction of the total costs. Condition (3) is a quota restriction that captures that total legal landings cannot exceed the quota. This restriction will always be binding when we focus on the case

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[5] Note also that we assume that firms obtain the same output price for fish landed illegally and legally. In reality, the marginal private value (price) of illegal landings may be lower than the price of legal landings, because of, for example suboptimal handling and processing of illegal landings. However, the analysis generalizes easily to the case where the price of legal landings differs from that of illegal landings.

where the firm harvests both legally and illegally (which is what we are interested in here). Condition (4) is a participation constraint, which expresses that agents must receive at least their reservation payoff, U^0, to participate. Thus, condition (4) implies that the firm wants the employees to work onboard the vessel.

Note that since the wage function enters with a negative sign in the firm's objective function, condition (4) will always bind. This implies that:

$$W(h_{Lt}, h_{It}) = U^0 + \alpha c(h_{Lt}, h_{It}, x_t) + \gamma G(h_{It}) \tag{5}$$

Equation (5) shows that the wage covers the employees' reservation payoff, their costs of working on board the vessel, and their expected penalty. From this, it follows that the firm insures the agent against all costs. One might argue that the employees should be able to increase the payoff by changing the harvested quantity. However, since there are no wage frictions in the base model, the firm will design a wage contract that ensures that the employees obtains the highest possible expected payoff by doing exactly what the principal wants them to do. Consequently, changing the harvest quantities away from the firm's desired level can only reduce the employees' expected payoff. In section 3.1 we show that this is no longer the case if the wage function is constrained.

Returning to the optimization problem of the firm, we can substitute (5) into (2), yielding the following modified maximization problem:

$$\max_{h_{Lt}, h_{It}} \left(p(h_{Lt} + h_{It}) - c(h_{Lt}, h_{It}, x_t) - U^0 - \gamma [G(h_{It}) + F(h_{It})] \right), \tag{6}$$

which must satisfy the quota constraint given by (3).

Assuming a binding quota restriction, implying that the firm considers illegal landings, the Lagrangian of the maximization problem in (6) and (3) becomes:

$$L = p(h_{Lt} + h_{It}) - c(h_{Lt}, h_{It}, x_t) - U^0 - \gamma [G(h_{It}) + F(h_{It})] + \varepsilon_t (Q_t - h_{Lt}) \tag{7}$$

where ε_t is a Lagrange multiplier that measures the shadow price of the quota restriction.

The first-order conditions with respect to legal and illegal landings, h_{Lt} and h_{It}, are:

$$\frac{\partial L}{\partial h_{Lt}} = p - \frac{\partial c}{\partial h_{Lt}} - \varepsilon_t = 0 \tag{8}$$

$$\frac{\partial L}{\partial h_{It}} = p - \frac{\partial c}{\partial h_{It}} - \gamma \left[F'(h_{It}) + G'(h_{It}) \right] = 0 \tag{9}$$

Both conditions (8) and (9) state that the marginal private benefit of landings, p, must equal the marginal private costs. The marginal private cost of legal landings (equation (8)) consists of the marginal production costs of firm and employee, $\partial c / \partial h_{Lt}$, and the shadow price of the quota constraint, ε_t. The marginal private cost of illegal landings (equation (9)) consists of the marginal production cost, and the marginal expected penalties of firm and employee. Note that the production costs and expected penalties of both firm and employees are included because the principal fully covers the costs of the agent.

Conditions (8) and (9) allow us to derive illegal harvest as a function of the inspection rate, the quota (legal harvest), and the stock. This relationship is given by $h_{It} = h_{It}(\gamma, Q_t, x_t)$, which can be considered the reaction function of the firm. It is straightforward to show that, given the properties of the harvest cost function, $c(h_{Lt}, h_{It}, x_t)$, and the penalty functions, $F(h_{It})$ and $G(h_{It})$, we must have that $\frac{\partial h_{It}}{\partial x_t} > 0$, $\frac{\partial h_{It}}{\partial \gamma} < 0$, and $\frac{\partial h_{It}}{\partial Q_t} < 0$.[6]

We can now derive society's enforcement cost function from the reaction function of the firm. We first invert the reaction function of the firm, which yields $\gamma = \gamma(h_{it}, Q_t, x_t)$. The inverted reaction function describes the link between the probability of being detected, illegal landings,

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[6] The proofs for sign of these derivatives are available in the appendix.

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stock size, and the quota.[7] Next, recall that $\gamma(e_t)$ describes the relationship between the probability of being detected and enforcement effort, with $\dfrac{\partial \gamma}{\partial e_t} > 0$. We can invert $\gamma(e_t)$ to get $e_t(\gamma)$, and by substituting in the inverted reaction function we get: $e_t = e_t(\gamma(h_{it}, Q_t, x_t)) = \alpha(h_{it}, Q_t, x_t)$. Finally, we introduce an enforcement cost function that depends on enforcement effort, $K(e_t)$, which we assume is increasing and convex in enforcement effort: $\dfrac{\partial K}{\partial e_t} > 0$ and $\dfrac{\partial^2 K}{\partial e_t^2} > 0$. Now, we can substitute $e_t = \alpha(h_{it}, Q_t, x_t)$ into the enforcement cost function, which yields $K(e_t) = K(e_t(\alpha(h_{it}, Q_t, x_t))) = E(h_{it}, Q_t, x_t)$. Thus, we have established that the total enforcement cost depends on the level of illegal landings, the quota, and the availability of fish. Given that the properties of the firm's reaction function, and particularly that $\dfrac{\partial \gamma}{\partial e_t} > 0$, and the properties of the enforcement cost function, we have that

$\dfrac{\partial E}{\partial x_t} > 0$, $\dfrac{\partial E}{\partial Q_t} < 0$, and $\dfrac{\partial E}{\partial h_{It}} < 0$.[8] Thus, all else equal, allowing for higher illegal landings implies a reduction in enforcement costs, while a larger stock leads to an increase in enforcement costs, all else equal. Finally, a higher quota reduces the enforcement costs. We will make use of the properties of the enforcement cost function when we analyze the social planner case below.

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[7] If we, for example, assume a given stock size and quota, the inverted reaction function describes the necessary probability of being detected to achieve a given level of illegal landings.

[8] We provide a detailed description of how we derive the enforcement cost function and its properties in the appendix.

2.2 Social planner problem

To find optimal aggregate illegal and legal landings at time t, h_{It} and h_{Lt}, we let a social planner maximize the present value of future resource rents for a representative vessel (firm) net of enforcement costs. Note that we include the full value of illegal landings in the welfare function, in line with Milliman (1986) and Lewin and Trumbull (1990) who conclude that the social planner should account for the value of regulatory offences in their analyses of the social value of criminal gains. Furthermore, we assume costless fines. On this basis, we can formulate the maximization problem of the social planner, with legal and illegal landings as control variables, and stock size, x_t, as the state variable:[9]

$$\max_{h_{Lt}, h_{It}} \int_{t=0}^{\infty} \left(p(h_{Lt} + h_{It}) - c(h_{Lt}, h_{It}, x_t) - E(h_{It}, h_{Lt}, x_t) \right) e^{-\delta t} dt , \qquad (10)$$

s.t.

$$f(x_t) - h_{Lt} - h_{It} = \dot{x}_t , \qquad (11)$$

where $\delta > 0$ is the discount rate, and $f(x_t)$ is a natural growth function. In equation (10), the enforcement cost function takes into account the behavioral response of the fishing firms to changes in the quota (legal harvest) and the stock size, and the corresponding impact of these variables on the enforcement costs to achieve a given combination of legal and illegal landings. We have already established that $\dfrac{\partial E}{\partial h_{It}} < 0$. In addition, we assume that the enforcement cost function is convex in the *reduction* of illegal landings, $\dfrac{\partial^2 E}{\partial h_{It}^2} > 0$. Furthermore, it is never

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[9] One might argue that it would be more appropriate in light of real-world fisheries management to let Q_t, and not h_{Lt} be the control variable. However, from section 2.1, we have that $h_{Lt} = Q_t$. In addition, it is useful to have the same control variable in sections 2.1 and 2.2. Thus, we chose to use h_{Lt} as the control variable throughout.

optimal to eliminate all illegal harvesting: $\lim_{h_{It} \to 0} e(h_{It}) = \infty$. The resource restriction (11) states

that the change in stock size ($\dot{x}_t$) must equal the natural growth of the fish stock net of

harvesting. For the natural growth function, we assume $f'(x_t) > 0$ for $0 < x < x_{msy}$, and

$f'(x_t) < 0$ for $x > x_{msy}$, where x_{msy} is the stock size corresponding with the maximum

sustainable yield, and finally that $f''(x_t) < 0$. A standard logistic growth function satisfies

these assumptions. The problem given by (10) and (11) gives an accurate representation of how

a socially optimal quota (h_{Lt}) should be determined.

Efforts to hide illegal activities (avoidance) and similar costly activities related to illegal

harvesting may create differences in harvest costs between legal and illegal fishing. Hence, the

presence of such costs implies that we should separate between legal and illegal harvests in the

cost function. Furthermore, if quota enforcement did not cost anything, the social planner

would eliminate all illegal harvesting in the social optimum, to avoid avoidance costs and

similarly incurred by illegal activity. However, in our model, as in real world fisheries (Arnason

et al., 2000), enforcement costs play a significant role. It typically becomes increasingly costly

to raise the detection rate marginally, and it is usually suboptimal to increase the detection rate

to a level that fully deters violations. We therefore focus on the case with imperfect

enforcement and quota violations in the following.

The current-value Hamiltonian of the problem defined by (10) and (11) is:

$$H = p\left(h_{Lt} + h_{It}\right) - c\left(h_{Lt}, h_{It}, x_t\right) - E\left(h_{Lt}, h_{It}, x_t\right) + \lambda_t \left(f(x_t) - h_{It} - h_{Lt}\right) \qquad (12)$$

where λ_t is a co-state variable that measures the marginal cost of the dynamic stock externality.

Note that this marginal cost depends on the current stock size, and will thus change over time

unless the fishery is in a steady-state equilibrium. Given our focus on non-compliance and

liability, it is sufficient to state the optimality conditions for the control variables (legal and illegal landings):

$$\frac{\partial H}{\partial h_{Lt}} = p - \frac{\partial c}{\partial h_{Lt}} - \frac{\partial E}{\partial h_{Lt}} - \lambda_t = 0 \qquad (13)$$

$$\frac{\partial H}{\partial h_{It}} = p - \frac{\partial c}{\partial h_{It}} - \frac{\partial E}{\partial h_{It}} - \lambda_t = 0 \qquad (14)$$

Conditions (13) and (14) state that the marginal social benefit, p_t, equals the total marginal social costs of legal and illegal landings, respectively. For both legal and illegal landings, the total marginal social cost consists of the marginal harvest cost ($\partial c / \partial h_t$, with $h_t = h_{Lt}, h_{It}$), the marginal enforcement cost ($\partial E / \partial h_t$, with $h_t = h_{Lt}, h_{It}$), and the marginal cost of the dynamic stock externality. Note that condition (13) is the condition for the optimal quota (legal landings), while (14) can be interpreted as the condition for optimal enforcement (illegal landings). Because of a non-constant λ_t over time, the optimal enforcement policy changes over time.

Above, we mentioned that due to for example avoidance costs, illegal fishing might be costlier than legal fishing. However, if enforcement costs are sufficiently high for it to be socially undesirable to fully deter all quota violations, there will be an interior solution involving both illegal and legal landings. Using this, we can use equations (13) and (14) to obtain a relationship between legal and illegal landings given by $\frac{\partial c}{\partial h_{Lt}} + \frac{\partial E}{\partial h_{Lt}} = \frac{\partial c}{\partial h_{It}} + \frac{\partial E}{\partial h_{It}}$. Hence, in the social optimum, the total marginal social cost (harvesting cost and enforcement cost) must be the same for legal and illegal landings.

2.3 Optimal liability

We can now compare the optimality conditions of the private and the social planner problems to investigate under which conditions the private solution is also socially optimal. Let us first consider legal landings, given by conditions (8) and (13). Alignment of social and private legal landings requires that:[10]

$$\varepsilon_t = \frac{\partial E}{\partial h_{Lt}} + \lambda_t, \tag{15}$$

Condition (15) implies that the firm's shadow price of the quota constraint, ε_t, must equal the marginal enforcement cost of the quota (legal landings) plus the marginal cost of the dynamic stock externality, λ_t. This will generally not hold in a decentralized fishery, but can be achieved through regulations. In the absence of enforcement costs ($\frac{\partial E}{\partial h_{Lt}} = 0$), we obtain that $\varepsilon_t = \lambda_t$.

From section 2.1, we have that $\frac{\partial E}{\partial h_{Lt}} = \frac{\partial E}{\partial Q_t} < 0$, which means that (15) implies that $\varepsilon_t < \lambda_t$.

Thus Q_t is larger with enforcement cost than without these costs, and this is explained by the fact that an increase in the quota reduces illegal landings, and thus, the enforcement costs.

Let us next analyze illegal landings. From the perspective of the social planner, the detection probability in the private optimality condition for illegal landings (9), depends on the exerted enforcement effort. From section 2.1, we have that enforcement effort in turn can be expressed as a function of stock size, legal and illegal landings, which implies that $\gamma = \gamma\left(\alpha(h_{Lt}, h_{It}, x_t)\right) = \mu\left(h_{Lt}, h_{It}, x_t\right)$. Then, by comparing conditions (9) and (14), we find that alignment of private and socially optimal illegal landings requires:

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[10] Note that $h_{Lt} = Q_t$, which implies that $\frac{\partial E}{\partial h_{Lt}} = \frac{\partial E}{\partial Q_t}$.

$$\mu\left(h_{It}, h_{Lt}, x_t\right)\left[F'(h_{It}) + G'(h_{It})\right] = \frac{\partial E}{\partial h_{It}} + \lambda_t. \tag{16}$$

Thus, the social planner must set the expected punishment so that the marginal enforcement cost of illegal landings plus the marginal cost of the dynamic stock externality equal the expected value of the marginal penalty for both firm and employee.[11] Since λ_t varies over time, we get from (16) that the optimal fine policy varies over time. We can calculate the optimal quotas and illegal landings by solving the equation system given by equations (15) and (16) for h_{It} and h_{Lt}. This, in turn, enables us to find the optimal enforcement level as a function of the optimal legal and illegal landings, and the current stock level. Finally, note that (15) and (16) represent a first-best optimum since there are no frictions in the wage function between firm and employees.

With this in place, we can investigate the implications of the allocation of liability. The mixed liability case is already reflected by equations (15) and (16). With full firm and full employee liability, respectively, either the employee pays no fine ($G(h_{It}) = G'(h_{It}) = 0$) or the firm pays no fine ($F(h_{It}) = F'(h_{It}) = 0$). Hence, in the case of full firm liability, equation (16) reduces to:

$$\mu\left(h_{It}, h_{Lt}, x_t\right) F'(h_{It}) = \frac{\partial E}{\partial h_{It}} + \lambda_t, \tag{17}$$

while in the case of full employee liability, equation (16) reduces to:

$$\mu\left(h_{It}, h_{Lt}, x_t\right) G'(h_{It}) = \frac{\partial E}{\partial h_{It}} + \lambda_t. \tag{18}$$

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[11] This result might be more likely to hold with fees than with quotas. Optimality with fees of legal and illegal landings requires that the fee is equal to the shadow price of the fish stock (Laffont and Tirole, 1993).

Regardless of the liability allocation, equation (16) remains unchanged. Equations (17) and (18), along with equations (15) and (16), show that a social planner can achieve a first-best solution under mixed liability, full firm liability, and full employee liability. Hence, the liability allocation does not matter. Regardless of whom the legal system holds liable for quota violations, the social planner can set the enforcement effort and the quota to secure an optimal outcome. The reason is the lack of frictions in the base. Hence, regardless of liability allocation, the firm can shift all relevant costs (including expected fines) fully between the firm and the employees, thereby leaving the employees equally well of regardless of the formal liability rule, at least in expectation terms.

Our main result thus far is therefore that we can reach a social optimum regardless of which actor the legal system holds liable for illegal landings. As mentioned above, the environmental economics literature reaches similar results assuming a static flow externality (Segerson and Tietenberg, 1992; de Vries and Franckx, 2012). However, we assume a dynamic stock externality by including a dynamic resource restriction, which represents a new contribution to this literature. Indeed, our analysis shows that the dynamic stock externality, and thus the status of the resource stock, affects the optimal quota and enforcement policy. Hence, the optimal policy in our study varies over time in contrast to the static policy considered in previous work.

The lack of frictions in our model drives our liability-irrelevance result, and particularly the assumptions that firms have full flexibility in specifying wage functions. Hence, the firm can dictate the behavior of its employees, while the regulator can dictate the behavior of the fishing firms. In the next section, we consider the consequences of introducing wage frictions between firm and employee through restrictions on the wage functions, and of assuming limited financial assets for firm and/or employees that diminishes the deterrence effect of fines. We show that social optimality relies critically on the firm's ability to shift the fine penalty to the employee.

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3. Extending the Benchmark Model

In the benchmark model, we assumed the firm have full flexibility when specifying the wage contract, and that both firm and employees had the necessary financial means to pay any fine. In this section, we relax these assumptions. We start out by analyzing the implications of compensating the employees according to the share-of-profit or share-of-revenue rules.[12] Sharing rules are commonly used remuneration schemes in fisheries, and we consider two of the more frequently used specifications. In the treatment of sharing rules, we continue to assume that firms and employees have the financial means to pay any fine. However, in section 3.2, we analyze the implications of imposing asset limitations in the base model.

3.1 The share system of remuneration

Before we implement the share systems of remuneration in the base model, it is useful to investigate how the firm induces the employees to harvest the desired quantity. Recall that we did not do this in the analysis of the base model, since we established that with full flexibility in designing the wage contract, the firm could induce its employees to harvest any quantity. Hence, we could do the analysis without analyzing exactly how the firm induced its firm to behave in a certain way.

The Lagrange function of the maximization problem of the employees is:

$$L_e = W\left(h_{Lt}, h_{It}\right) - \alpha c\left(h_{Lt}, h_{It}, x_t\right) - \gamma G\left(h_{It}\right) + u_t\left(Q_t - h_{Lt}\right), \tag{19}$$

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[12] Our focus in this section is on the socially optimal design of liability rules given a certain sharing rule. Therefore, our analysis differs from the principal-agent literature on remuneration schemes in fisheries (Bergland, 1995; Matthiasson, 1999; Nguyen and Leung, 2009; Thue *et al.*, 2013).

where u_t is the employees' shadow price of the quota constraint.[13] Thus, the employees also account for the quota restriction. The employees' first order conditions for legal and illegal landings are:

$$\frac{\partial L_e}{\partial h_{Lt}} = \frac{\partial W}{\partial h_{Lt}} - \alpha \frac{\partial c}{\partial h_{Lt}} - u_t = 0 \tag{20}$$

$$\frac{\partial L_e}{\partial h_{It}} = \frac{\partial W}{\partial h_{It}} - \alpha \frac{\partial c}{\partial h_{It}} - \gamma G'(h_{It}) = 0 \tag{21}$$

Assuming, as in the base model, that the quota constraint binds ($h_{Lt} = Q_t$), equation (20) determines legal landings. In addition, and as discussed above, the employees' participation constraint must hold. Hence, the fishing firm can determine the appropriate compensation scheme by ensuring that the reaction functions of the employees for legal and illegal landings (equations (20) and (21)) correspond with the firm's optimal levels of legal and illegal landings (equations (8) and (9)).

With restrictions on the wage function, the firm might no longer be able to induce the employees to harvest any desired quantity. If this is the case, equations (20) and (21) will determine the harvest quantity rather than equations (8) and (9) as in the base model. Under the share-of-profit system, the employees receive a share of the firm's profits from the fishing operation, while they receive a share of revenues in the share-of-revenue system. We will show that while a social planner can secure a second-best optimum under profit sharing by proper choice of quota and liability allocation, only full employee liability ensures the same with revenue sharing. Assume that depending on which share system we consider, the employees receive at least a fraction β_1 of the firm's expected profit or a fraction β_2 of the firm's revenue.

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[13] Note that since the employees, just like the firms, are myopic decision makers, they do not take into account the future availability of fish (or the shadow price of the resource constraint).

In both cases, either the agent's participation constraint (4) or the wage scheme must bind. Let us assume the wage scheme binds. Then, under profit and revenue sharing, respectively, we have that:

$$W\left(h_{Lt},h_{It}\right)=\beta_1\left[p_t\left(h_{Lt}+h_{It}\right)-\left(1-\alpha\right)c\left(h_{Lt},h_{It},x_t\right)-\gamma F\left(h_{It}\right)\right] \tag{22}$$

$$W\left(h_{Lt},h_{It}\right)=\beta_2\left(p_t\left(h_{Lt}+h_{It}\right)\right). \tag{23}$$

In line with our analysis of the base model, the firm remunerates the employees based on both legal and illegal harvesting. In the case of profit sharing, this implies that the wage function includes the firm's expected penalty, $\gamma F_t\left(h_{It}\right)$. The difference between the share-of-profit and share-of-revenue systems is that the latter does not include the firm's costs, and hence, allows for no shifting of costs between the principal and the agent.

The wage functions (22) and (23) can be substituted into the firm's profit function (2). However, since the share systems leaves the firm with only one choice variable, the profit- and revenue-sharing parameters β_1 and β_2, respectively, the firm cannot dictate the harvest levels of the employees. To see this, note that the sharing parameters enter linearly into both the agent's and the principal's optimization problems, regardless of the share system. Hence, the firm can only use the share parameter to influence whether the employees work on-board the vessel, but cannot use the wage incentive to influence their harvesting efforts. It follows that it will be optimal for the firm to pay its employees the lowest possible share that ensures that they will work on-board the vessel, as given by the participation constraint (4), while it can only hope the employees will harvest close to the desired quantity.

With the employees determining legal and illegal landings, we must consider their decisions when deriving the conditions for optimal quotas and liability. The Lagrange function of the representative agent's optimization problem, given that the participation constraint holds, is the

same as in the base model (7), but with the share wage functions (22) or (23), replacing the flexible wage function $W\left(h_{Lt},h_{It}\right)$.

We can now use the employees' optimality conditions, equations (20) and (21), to determine h_{Lt} and h_{It}. Specifically, we can derive a reaction function, $h_{It}=h_{It}(Q_t,\gamma,x_t)$, from the optimality conditions of the employees for each of the two sharing rules. Although these reaction functions will differ from the one we derived for the firm above based on the base model, it is straightforward to show that given the properties of the harvest cost and the penalty functions, the reaction function must satisfy: $\dfrac{\partial h_{It}}{\partial x_t}>0$, $\dfrac{\partial h_{It}}{\partial \gamma}<0$, and $\dfrac{\partial h_{It}}{\partial Q_t}<0$. These properties match the properties of the reaction function derived for the base model, and hence, as in section 2, we must have that $\dfrac{\partial E}{\partial x_t}>0$, $\dfrac{\partial E}{\partial Q_t}<0$, and $\dfrac{\partial E}{\partial h_{It}}<0$.[14] This implies that we can compare the private outcomes to the social planner optimum given by equations (13) and (14), even though the underlying enforcement cost functions differ.

Let us now consider the optimal selection of policy instruments for the share-of profit case. Comparing the private and social optimality conditions in this case yields the following conditions:

$$\frac{\partial E}{\partial h_{Lt}}+\lambda_t=u_t+\left(1-\beta_1\right)p-\left(1-\alpha\right)\left(1-\beta_1\right)\frac{\partial c}{\partial h_{Lt}} \tag{24}$$

$$\frac{\partial E}{\partial h_{It}}+\lambda_t=\mu\left(h_{Lt},h_{It},x_t\right)\left(\beta_1 F'(h_{It})+G'(h_{It})\right)+\left(1-\beta_1\right)p-\left(1-\alpha\right)\left(1-\beta_1\right)\frac{\partial c}{\partial h_{It}} \tag{25}$$

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[14] Detailed derivation of both the reaction function and enforcement cost function and their properties are available in the appendix.

where we in (25) have used that from the perspective of the social planner, $\gamma = \gamma\left(\alpha(h_{Lt}, h_{It}, x_t)\right) = \mu\left(h_{Lt}, h_{It}, x_t\right)$, as in the base model. Doing the same comparison for the share-of-revenue case yields:

$$\frac{\partial E}{\partial h_{Lt}} + \lambda_t = u_t + \left(1 - \beta_2\right) p_t - \left(1 - \alpha\right)\frac{\partial c}{\partial h_{Lt}} \tag{26}$$

$$\frac{\partial E}{\partial h_{It}} + \lambda_t = \mu(h_{Lt}, h_{It}, x_t)G_t'\left(h_{It}\right) + \left(1 - \beta_2\right) p_t - \left(1 - \alpha\right)\frac{\partial c}{\partial h_{It}}. \tag{27}$$

Due to wage frictions between the firm and the employees, the optimal policy conditions for the two sharing rules, represent second-best solutions. Let us start out by considering the optimal quota policies for the two sharing rules. Recall that in the base model, the optimal quota condition stated that the private shadow price of the quota should equal the marginal enforcement cost plus the marginal cost of the dynamic stock externality (equation (16)). However, when a sharing rule determines wages, two additional terms enter into the optimal quota condition (equations (24) and (26)): the marginal revenue and marginal costs of the firm. We must include these terms because there is no mechanism for transferring the relevant costs and benefits from firm to employees. The wage friction causes an externality where the employees ignore the effect of their harvesting choices on the firm. Thus, the social planner chooses quotas and fines to internalize this externality. There is one difference between the optimal quota policies under profit sharing (24) and revenue sharing (26). With profit sharing, the social planner only correct for a share $1 - \beta_1$ of the marginal harvesting cost of the firm, since profit sharing already shifts a share β_1 of the firm's harvesting costs to the employees, while we correct for the full marginal cost in the revenue-sharing case.

Let us now turn to the optimality conditions for illegal landings (enforcement), as given by equations (25) and (27). In the base model, the optimality condition for illegal landings states

that the marginal enforcement cost plus the marginal cost of the dynamic stock externality should equal the marginal expected penalties of firm and employees (equation (16)). Again, with the wage frictions introduced by the sharing rules, the social planner must correct for the fact that the employees do not take into account the implications of their harvesting decision for the firm. In this case, two additional terms enter into the optimal enforcement condition, representing the firm's shares of marginal revenue and marginal costs. In addition, the marginal expected penalty that enters into the condition depends on which of the two sharing rules we consider. With profit sharing, the optimal enforcement condition (25) includes the marginal expected penalty paid by the employees directly, $G'(h_{It})$, and indirectly through the wage function, $\beta_1 F'(h_{It})$, while with revenue sharing, condition (27) only includes the marginal expected penalty of the employee. As for the optimal quota conditions, we can explain these differences by the differences in underlying wage functions, and hence, for both the optimal quotas and fines, the optimal policy shifts the relevant costs from the principal to the decision-making agent. From (12) we know that λ_t is non-constant over time, and so the optimal enforcement and fine policies given by (25) and (27) must also vary over time.

Let us now investigate the implications of liability allocation between firm and employees. With revenue sharing, the optimal enforcement condition (27) contains the expected penalty function of the employee but not the firm. This implies that only full employee liability can ensure a second-best optimum. With profit sharing, the social planner can ensure a second-best optimum given by equations (24) and (25), regardless of liability allocation. While the optimality condition for quota (24) is unaffected by the allocation of liability, this is not the case for the optimality condition for enforcement (25). With mixed liability the optimal enforcement policy is given by equation (25), the term $G'(h_{It})$ drops out of (25) with full firm liability, and the term $F'(h_{It})$ drops out with full employee liability. Hence, the optimal quota

and enforcement policy might differ depending on whether the enforcement system penalizes the firm, the employee, or both for illegal landings.

Let us finally consider the special case when the firm cannot shift expected penalties to its employees. This implies that the wage function in (22) cannot include the term $\gamma F\left(h_{It}\right)$. This only changes the liability analysis for the share-of-profit case. Without the ability to shift a part of the expected fine to the employees under profit sharing, only employee liability ensures a second-best optimum. To see this, note that condition (24) is unchanged while $\beta F'(h_{It})$ drops out of equation (25). Hence, firm liability cannot work. However, $G'(h_{It})$ is included in equation (25), and so employee liability can secure a second-best optimum. When the firm cannot shift the expected fine to the employees, the employees do not consider $\beta F'(h_{It})$ when making decisions about illegal landings. Hence, changes in the firm's expected fine will not affect the level of illegal landings.

In this section, we have shown that both the share-of-profit and the share-of-revenue rules can ensure a second-best optimum. However, while the allocation of liability does not matter with a share-of-profit rule, only agent liability yields the efficient outcome with a share-of-revenue rule. Hence, a sharing rule that allows the firm to share both costs and revenues with the employee makes it less critical which liability scheme the industry faces.

3.2 Limited assets

In the base model, we assume that firm and employees have unlimited assets. However, in reality both parties may face an upper limit on the fines they are able to pay, and this might change the optimal punishment and cause inefficiencies. Therefore, we now analyze the implications of asset limitations for both firm and employees, and discuss indemnification clauses for the employees within the modeling framework from section 2.

Let V_t and L_t denote the financial assets available to the employees and the firm, respectively, at time t. Introducing an asset constraint for the *employees* implies that the fine must fulfill the condition:

$$G(h_{It}) \leq W(h_{Lt}, h_{It}) - \alpha c(h_{Lt}, h_{It}, x_t) + V_t \, , \tag{28}$$

Note that in condition (28) the actual penalty rather than the expected penalty enters (see section 2). When interpreting equation (28), we distinguish between two cases characterized by whether the firm can offer the employee an indemnification clause. With an indemnification clause the firm covers any fines paid by the employee for illegal harvesting. Therefore, condition (28) is non-binding, and because $G(h_{It}) \geq \gamma G(h_{It})$, the analysis from section 2 applies. Hence, with indemnification clauses, the manager can ensure a first-best optimum with all liability rules. Thus, provided the firm does not have a binding asset constraint, an indemnification clause is optimal in fisheries.[15] Turning to the case without indemnification clauses, full employee liability cannot secure a first-best optimum once the penalty exceeds the employee's asset constraint. This result holds even with full wage flexibility as the firm only can compensate the employees for the expected fine, not for the actual fine. However, full firm liability will work since the firm does not face a binding asset restriction. Turning to mixed liability, equations (15), (28) and (29) determine the outcome provided the employees' asset restriction in (28) is binding. In this case, increasing the employees' fine, $G(h_{It})$, beyond the level characterized by condition (28) has no deterrence effect. Hence, once the asset constraint in equation (28) binds, a further increase in the employees' formal fine does not increase the

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[15] A similar result is reached in a general cooperate crime model by Kornhauser (1982).

actual fine payment, and therefore, we have that $G'(h_{It}) = 0$. Next, we can find the firm's fine

from condition (16) with $G'(h_{It}) = 0$, which yields:

$$\mu\left(h_{It}, h_{Lt}, x_t\right) F'(h_{It}) = \frac{\partial E}{\partial h_{It}} + \lambda_t \qquad (29)$$

Hence, equations (28) and (29) determine the second-best optimal enforcement policy with

mixed liability, while equation (15) determines the optimal quota.

Similarly, with a binding asset constraint for the firm, the optimal enforcement policy must

satisfy the following two conditions:

$$F(h_{It}) \leq p(h_{Lt} + h_{It}) - (1-\alpha)c(h_{LT}, h_{It}, x_t) - W(h_{LT}, h_{It}) + L_t \ , \qquad (30)$$

$$\mu(h_{Lt}, h_{It}, x_t)G'(h_{It}) = \frac{\partial E}{\partial h_{It}} + \lambda_t \ . \qquad (31)$$

Note first that if the actual penalty can be shifted from the firm to the employee, condition (31)

never binds, which means that it does not matter who is held liable (see section 2). Next, if the

firm cannot shift the fine to the employee, which is perhaps the more plausible case for the

fishing industry, full employee liability will still work, since this case is unaffected by the asset

constraint of the firm. With full firm liability, the fine should be set to the maximum allowed

by the asset constraint (30), but this will generally not yield the optimal solution. However,

under mixed liability, we can achieve a second-best optimum by ensuring that equations (30)

and (31) hold simultaneously along with the optimal quota condition (15).

Finally, if both firm and employees face binding asset constraints, equations (28) and (30)

determine the fines. In this case, the fines will be too low to ensure the social optimum

regardless of indemnification clauses or wage contracts, and hence, irrespective of liability rule

(firm, employee, or mixed) the social planner cannot secure an optimum. Thus, in situations

where the firm and employees have limited assets, we can conclude that enforcement policies

are ineffective. We have seen examples of this in real-world fisheries, for example in cases

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when owners of "flag of convenience" vessels arrested for illegal fishing abandon their vessel rather than paying the fines (Agnew, 2000).

4. Concluding Remarks

The purpose of this paper was to analyze how the allocation of liability between fishing firms and their crew affects quota violations and the ability to design a socially efficient fisheries policy. Contrary to the existing fisheries economics literature on enforcement, which typically treats the fishing firm or vessel as one individual decision maker, we model noncompliance in a principal-agent framework where the firm and its crew may have conflicting interests. Relative to the previous fisheries economic enforcement literature, this enables us to investigate new factors and relationships that affect regulatory compliance in fisheries.

We develop a model in which the firm receives the revenues from the fish landed by its vessel. The crew, on the other hand, operates the vessel and make the harvesting decisions. Hence, while only the firm benefits directly from quota violations, the crew make the decision of whether and how much to violate. The firm must therefore use the compensation scheme to induce the crew to act in its best interest, which may include landing fish illegally. To consider the implication of different liability allocation rules, we investigate the incentive structure between the firm and the crew. Without wage frictions, the firm can induce the crew to land any given quantity through the compensation scheme. This makes the firm the real decision maker, and hence, holding the firm liable for quota violations can yield the socially optimal outcome. However, in the absence of wage frictions, we can achieve the same with full crew liability, or with a combination of firm and crew liability. The reason is that when the firm can shift all relevant benefits and costs, including expected fines, between it-self and the crew and it is thus irrelevant who is (formally) held liable for illegal activities.

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The irrelevance result for the allocation of liability in the absence of wage frictions, is in line with the environmental economic literature on liability. However, while studies on liability in the setting of environmental regulations consider a static flow externality, we investigate the implications of a dynamic stock externality. This externality expresses that neither the crew nor the firm takes the future availability of fish into account when making harvest decisions. The marginal cost of this dynamic stock externality depends on the current size of the resource stock, and will therefore change over time unless the fishery reaches a steady-state equilibrium. This implies that the optimal enforcement policy also changes over time. Hence, extending the liability result to the case of fisheries and other renewable resources represents a novel contribution to this literature.

Next, we introduce wage frictions by analyzing the share system of remuneration, which is commonly used in fisheries. We show that when there are wage frictions that restricts the firm from shifting relevant benefits and costs to/from the employees, the liability irrelevance result might break down. We consider two specific constraints on the wage function; the share-of-profit and the share-of-revenue systems of remuneration. Both sharing rules severely restricts the ability of the firm to influence the employees' harvesting behavior through the wage. We show that only agent liability can guarantee a second-best optimum under revenue sharing and under profit sharing when penalties cannot be shifted from the firm to the employee. Finally, we analyze the implications of the firm and the employees facing financial constraints that limit how large actual fine payments they can make. Perhaps not surprisingly, this restricts who can be held liable and to what extent, which may reduce our ability to ensure an efficient solution. Our results show that with the proper selection of quotas, fines, and liability rules, one can reach the socially optimal outcome in almost every case we have investigated. However, in most fisheries, as in other industries, the allocation of liability for regulatory violations is not the choice of a regulator (or social planner) but rather determined by the legal system. Thus,

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we do not intend to provide policy advice in terms of optimal liability rules in this paper, but instead we point out some relationships between liability, enforcement, and quotas, on the one hand, and quota violations, on the other.

Although we analyze for the case of fisheries, the results in the paper generalize beyond the fisheries case in two ways. First, we study the case when the firm rather than the employees benefits directly from illegal behavior. The employees, on the contrary, can only benefit through the compensation scheme. With few exceptions, the existing liability literature focuses instead on the case in which the employees and not the firm directly benefits from violations. For many renewable resources (e.g. water and forestry) and environmental externalities (e.g. illegal waste dumping), the setup in which the firm benefits from the violation gives a more accurate representation of the realities. Second, we consider a dynamic stock externality, which is highly relevant for a number of environmental problems, such as problems involving damaging pollution stocks (e.g. CO_2, NO_x, and particulate matter). As we have shown in this paper, such problems require enforcement policies that evolve over time with the current stock of the pollution stock, and thus the shadow price of pollution.

The introduction of principal-agent theory into the analysis of non-compliance in fisheries offers many possibilities for future work. One such possibility is to consider the effect of various risk attitudes on the behavior of the firm and the crew. In the current paper, we assume that everyone is risk neutral. The results might change if firm and crew are risk averse, or if for example individual crew members are more risk averse than the firm. Incorporating moral hazard between the firm and the crew might also yield new insights.

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APPENDIX

Appendix A: The basic model

A.1. Reaction functions

In this section, we derive and characterize the reaction functions presented and analyzed in the paper.

From the main text, the cost function satisfies the following properties:

$$\frac{\partial c}{\partial h_{Lt}} > 0, \frac{\partial^2 c}{\partial h_{Lt}^2} > 0, \frac{\partial c}{\partial h_{It}} > 0, \frac{\partial^2 c}{\partial h_{It}^2} > 0, \frac{\partial^2 c}{\partial h_{Lt}\partial h_{It}} > 0, \frac{\partial c}{\partial x_t} < 0, \frac{\partial^2 c}{\partial h_{It}\partial x_t} < 0, \frac{\partial^2 c}{\partial h_{Lt}\partial x_t} < 0 \qquad (A1)$$

In addition, the properties of the penalty functions are:

$$G'(h_{It}) > 0, \; G''(h_{It}) > 0, \; F'(h_{It}) > 0, F''(h_{It}) > 0 \qquad (A2)$$

From section 2.1, we have the following first-order conditions for the private optimum:

$$p - \frac{\partial c}{\partial h_{Lt}} - \varepsilon_t = 0 \qquad (A3)$$

$$p - \frac{\partial c}{\partial h_{It}} - \gamma \left[F'(h_{It}) + G'(h_{It}) \right] = 0 \qquad (A4)$$

$$h_{Lt} = Q_t \qquad (A5)$$

We can express the equation system (A3)-(A5) as the reaction function presented in the main text:

$$h_{It} = h_{It}(Q_t, x_t, \gamma) \qquad (A6)$$

Total differentiating (A3)-(A5) yields the following:

$$\frac{\partial^2 c}{\partial h_{Lt}^2} dh_{Lt} + \frac{\partial^2 c}{\partial h_{Lt}\partial h_{It}} dh_{It} + d\varepsilon = -\frac{\partial^2 c}{\partial h_{Lt}\partial x_t} dx_t \qquad (A7)$$

$$\frac{\partial^2 c}{\partial h_{Lt}\partial h_{It}} dh_{Lt} + [\frac{\partial^2 c}{\partial h_{It}^2} + \gamma(F''(h_{It}) + G''(h_{It}))]dh_{It} =$$

$$-\frac{\partial^2 c}{\partial h_{It}\partial x_t} dx_t - [F'(h_{It}) + G'(h_{It})]d\gamma \qquad (A8)$$

$$dh_{Lt} = dQ_t \tag{A9}$$

Inserting equation (A9) into (A7) and (A8) yields:

$$\frac{\partial^2 c}{\partial h_{Lt} \partial h_{It}} dh_{It} + d\varepsilon = -\frac{\partial^2 c}{\partial h_{Lt} \partial x_t} dx_t - \frac{\partial^2 c}{\partial h_{Lt}^2} dQ_t \tag{A10}$$

$$[\frac{\partial^2 c}{\partial h_{It}^2} + \gamma(F''(h_{It}) + G''(h_{It}))]dh_{It} = -\frac{\partial^2 c}{\partial h_{It} \partial x_t} dx_t - [F'(h_{It}) + G'(h_{It})]d\gamma - \frac{\partial^2 c}{\partial h_{Lt} \partial h_{It}} dQ_t \tag{A11}$$

Note that equation (A11) only depends on dh_{It}. Using this equation, we can now find $\dfrac{dh_{It}}{dx_t}$ by setting

$d\gamma = dQ_t = 0$:

$$\frac{dh_{It}}{dx_t} = -\frac{\dfrac{\partial^2 c}{\partial h_{It} \partial x_t}}{\dfrac{\partial^2 c}{\partial h_{It}^2} + \gamma(F''(h_{It}) + G''(h_{It}))} \tag{A12}$$

In (A12), the denominator is positive because $0 < \gamma < 1$, $\dfrac{\partial^2 c}{\partial h_{It}^2} > 0$, $F''(h_{It}) > 0$, and $G''(h_{It})$ (cf. equations

(A1) and (A2)). From (A1) we also have that $\dfrac{\partial^2 c}{\partial h_{It} \partial x_t} < 0$, which implies that $\dfrac{dh_{It}}{dx_t} > 0$.

Turning to $\dfrac{dh_{It}}{d\gamma}$, we set $dx_t = dQ_t = 0$ in (A11) and obtain:

$$\frac{dh_{It}}{d\gamma} = -\frac{[F'(h_{It}) + G'(h_{It})]}{\dfrac{\partial^2 c}{\partial h_{It}^2} + \gamma(F''(h_{It}) + G''(h_{It}))} \tag{A13}$$

The denominator is identical to the one in equation (A12), and is thus positive, and from (A2) we have that

$G'(h_{It}) > 0$ and $F'(h_{It}) > 0$. Consequently, we find that $\dfrac{dh_{It}}{d\gamma} < 0$.

Let us finally determine the effect of quota on illegal harvest. We let $d\gamma = dx_t = 0$ in (A11), and arrive at:

$$\frac{dh_{It}}{dQ_t} = -\frac{\dfrac{\partial^2 c}{\partial h_{Lt} \partial h_{It}}}{\dfrac{\partial^2 c}{\partial h_{It}^2} + \gamma(F''(h_{It}) + G''(h_{It}))} \tag{A14}$$

From before, we know that both the denominator and the numerator are positive, since $\dfrac{\partial^2 c}{\partial h_{Lt} \partial h_{It}} > 0$. This

implies that $\dfrac{dh_{It}}{dQ_t} < 0$.

A.2 Enforcement costs

In this section, we derive and characterize the enforcement cost function used in the paper.

We start out by inverting the reaction function in (A6), which yields:

$$\gamma = \gamma(Q_t, x_t, h_{It}) \tag{A15}$$

Total differentiating (A15) produces:

$$\frac{\partial \gamma}{\partial Q} dQ_t + \frac{\partial \gamma}{\partial x_t} dx_t + \frac{\partial \gamma}{\partial h_{It}} dh_{It} = 0 \tag{A16}$$

Next, we define the probability of being detected as a function of enforcement effort, $\gamma(e_t)$, and we assume

that:

$$\frac{\partial \gamma}{\partial e_t} > 0 \tag{A17}$$

Note that we can invert $\gamma(e_t)$ to yield $e_t(\gamma)$, and because of (A17) we obtain the following:

$$\frac{\partial e_t}{\partial \gamma} = \frac{1}{\dfrac{\partial \gamma}{\partial e_t}} > 0 \tag{A18}$$

Substituting the inverted reaction function into $e_t(\gamma)$ gives $e_t = e_t(\gamma(Q_t, x_t, h_{It})) = \alpha(Q_t, x_t, h_{It})$. Now, we

want to find the sign of the derivatives of $\alpha(Q_t, x_t, h_{It})$. First, we investigate the sign of $\dfrac{\partial \alpha}{\partial h_{It}}$ by using:

$$\frac{\partial \alpha}{\partial h_{It}} = \frac{\partial e_t}{\partial \gamma} \frac{\partial \gamma}{\partial h_{It}} \tag{A19}$$

From (A18), we have that $\dfrac{\partial e_t}{\partial \gamma} > 0$ and we note that:

$$\frac{\partial \gamma}{\partial h_{It}} = \frac{1}{\dfrac{\partial h_{It}}{\partial \gamma}} \tag{A20}$$

From (A13) we have that $\dfrac{\partial h_{It}}{\partial \gamma} < 0$, and consequently, from (A20) we get that $\dfrac{\partial \gamma}{\partial h_{It}} < 0$. Using (A19) now

implies that $\dfrac{\partial \alpha}{\partial h_{It}} < 0$.

Concerning the sign of $\dfrac{\partial \alpha}{\partial x_t}$ we have that:

$$\frac{\partial \alpha}{\partial x_t} = \frac{\partial e_t}{\partial \gamma} \frac{\partial \gamma}{\partial x_t} \tag{A21}$$

As above $\dfrac{\partial e_t}{\partial \gamma} > 0$. By setting $dQ_t = 0$ in (A16) and solving for $\dfrac{\partial \gamma}{\partial x_t}$ we reach:

$$\frac{\partial \gamma}{\partial x_t} = -\frac{\dfrac{\partial h_{It}}{\partial x_t}}{\dfrac{\partial h_{It}}{\partial \gamma}} \tag{A22}$$

From (A12), we know that $\dfrac{\partial h_{It}}{\partial x_t} > 0$, and from (A20) that $\dfrac{\partial h_{It}}{\partial \gamma} < 0$. Combining this with (A22) gives us that

$\dfrac{\partial \gamma}{\partial x_t} > 0$, which in turn implies that $\dfrac{\partial \alpha}{\partial x_t} > 0$.

Finally, we find the sign of $\dfrac{\partial \alpha}{\partial Q_t}$ by using that:

$$\frac{\partial \alpha}{\partial Q_t} = \frac{\partial e_t}{\partial \gamma} \frac{\partial \gamma}{\partial Q_t} \tag{A23}$$

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Setting $dx_t = 0$ in (A16) and solving for $\dfrac{\partial \gamma}{\partial Q_t}$ we get:

$$\frac{\partial \gamma}{\partial Q_t} = -\frac{\dfrac{\partial h_{It}}{\partial Q_t}}{\dfrac{\partial h_{It}}{\partial \gamma}} \tag{A24}$$

We have established that $\dfrac{\partial h_{It}}{\partial \gamma} < 0$, and from (A14) we learned that $\dfrac{\partial h_{It}}{\partial Q_t} < 0$. Therefore, (A24) implies that

$\dfrac{\partial \gamma}{\partial Q_t} < 0$, and using this in (A23) gives us that $\dfrac{\partial \alpha}{\partial Q_t} < 0$.

Let us next turn to the enforcement cost function, $K(e_t)$. We assume that:

$$\frac{\partial K}{\partial e_t} > 0 \text{ and } \frac{\partial^2 K}{\partial e_t^2} > 0 \tag{A25}$$

From above $e_t = e_t(\gamma(Q_t, x_t, h_{It})) = \alpha(Q_t, x_t, h_{It})$ and inserting this into the enforcement cost function gives

$K(e_t(\gamma(Q_t, x_t, h_{It}))) = F(\alpha(Q_t, x_t, h_{It})) = E(Q_t, x_t, h_{It})$. We now want to determine the signs of the

derivatives of the enforcement cost function, and we start by considering $\dfrac{\partial E}{\partial Q_t}$:

$$\frac{\partial E}{\partial Q_t} = \frac{\partial F}{\partial \alpha}\frac{\partial \alpha}{\partial Q_t} = \frac{\partial K}{\partial e_t}\frac{\partial e_t}{\partial \gamma}\frac{\partial \gamma}{\partial Q_t} \tag{A26}$$

From (A23), $\dfrac{\partial \alpha}{\partial Q_t} = \dfrac{\partial e_t}{\partial \gamma}\dfrac{\partial \gamma}{\partial Q_t} < 0$, and from (A25) we have that $\dfrac{\partial K}{\partial e_t} > 0$, which implies that $\dfrac{\partial E}{\partial Q_t} < 0$.

Next, for $\dfrac{\partial E}{\partial x_t}$ we have that:

$$\frac{\partial E}{\partial x_t} = \frac{\partial F}{\partial \alpha}\frac{\partial \alpha}{\partial x_t} = \frac{\partial K}{\partial e_t}\frac{\partial e_t}{\partial \gamma}\frac{\partial \gamma}{\partial x_t} \tag{A27}$$

Using (A21), we have that $\dfrac{\partial \alpha}{\partial x_t} = \dfrac{\partial e_t}{\partial \gamma} \dfrac{\partial \gamma}{\partial x_t} > 0$, and according to (A25), $\dfrac{\partial K}{\partial e_t} > 0$, from which it follows that

$$\frac{\partial E}{\partial x_t} > 0 .$$

Finally, for $\dfrac{\partial E}{\partial h_{It}}$ we get:

$$\frac{\partial E}{\partial h_{It}} = \frac{\partial F}{\partial \alpha} \frac{\partial \alpha}{\partial h_{It}} = \frac{\partial K}{\partial e_t} \frac{\partial e_t}{\partial \gamma} \frac{\partial \gamma}{\partial h_{It}} \tag{A28}$$

From (A19) we know that $\dfrac{\partial \alpha}{\partial h_{It}} = \dfrac{\partial e_t}{\partial \gamma} \dfrac{\partial \gamma}{\partial h_{It}} < 0$, and using (A23) we have that $\dfrac{\partial K}{\partial e_t} > 0$. This implies that

$$\frac{\partial E}{\partial h_{It}} < 0 .$$

Appendix B: Share of profit

B.1. Reaction functions

From section 3 we have the following first-order conditions:

$$\frac{\partial W}{\partial h_{Lt}} - \alpha \frac{\partial c}{\partial h_{Lt}} - u_t = 0 \tag{B1}$$

$$\frac{\partial W}{\partial h_{It}} - \alpha \frac{\partial c}{\partial h_{It}} - \gamma G'(h_{It}) = 0 \tag{B2}$$

$$h_{Lt} = Q_t \tag{B3}$$

We also have the following wage scheme from section 3:

$$W(h_{Lt}, h_{It}) = \beta \left[p_t (h_{Lt} + h_{It}) - (1-\alpha)c(h_{Lt}, h_{It}, x_t) - \gamma F(h_{It}) \right] \tag{B4}$$

From the wage scheme in (B4) we may obtain:

$$\frac{\partial W}{\partial h_{Lt}} = \beta (p - (1-\alpha)\frac{\partial c}{\partial h_{Lt}}) \tag{B5}$$

$$\frac{\partial W}{\partial h_{It}} = \beta (p - (1-\alpha)\frac{\partial c}{\partial h_{It}} - \gamma F'(h_{It})) \tag{B6}$$

(B5) can be substituted into (B1) and (B6) into (B2). This gives the following rewritten first-order conditions:

$$\beta (p - \frac{\partial c}{\partial h_{Lt}}) - (1-\beta)\alpha \frac{\partial c}{\partial h_{Lt}} - u_t = 0 \tag{B7}$$

$$\beta (p - \frac{\partial c}{\partial h_{It}}) - (1-\beta)\alpha \frac{\partial c}{\partial h_{It}} - \gamma(\beta F'(h_{It}) + G'(h_{It})) = 0 \tag{B8}$$

$$h_{Lt} = Q_t \tag{B9}$$

(B7) - (B9) may be total differentiated which gives:

$$[\beta \frac{\partial^2 c}{\partial h_{Lt}^2} + (1-\beta)\alpha \frac{\partial^2 c}{\partial h_{Lt}^2}]dh_{Lt} + [\beta \frac{\partial^2 c}{\partial h_{It}\partial h_{Lt}} + (1-\beta)\alpha \frac{\partial^2 c}{\partial h_{It}\partial h_{Lt}}]dh_{It} +$$

$$du_t = -[\beta \frac{\partial^2 c}{\partial h_{Lt}\partial x_t} + (1-\beta)\alpha \frac{\partial^2 c}{\partial h_{Lt}\partial x_t}]dx_t \tag{B10}$$

$$[\beta \frac{\partial^2 c}{\partial h_{It}\partial h_{Lt}} + (1-\beta)\alpha \frac{\partial^2 c}{\partial h_{It}\partial h_{Lt}}]dh_{Lt} + [\beta \frac{\partial^2 c}{\partial h_{It}^2} + (1-\beta)\alpha \frac{\partial^2 c}{\partial h_{It}^2} +$$

$$\gamma(\beta F''(h_{It}) + G''(h_{It}))]dh_{It} = -(\beta F'(h_{It}) + G'(h_{It}))d\gamma - \tag{B11}$$

$$[\beta \frac{\partial^2 c}{\partial h_{It}\partial x_t} + (1-\beta)\alpha \frac{\partial^2 c}{\partial h_{It}\partial x_t}]dx_t$$

$$dh_{Lt} = dQ_t \tag{B12}$$

(B12) can be substituted into (B10) and (B11) which gives:

$$+[\beta \frac{\partial^2 c}{\partial h_{It}\partial h_{Lt}} + (1-\beta)\alpha \frac{\partial^2 c}{\partial h_{It}\partial h_{Lt}}]dh_{It} + du_t =$$

$$-[\beta \frac{\partial^2 c}{\partial h_{Lt}\partial x_t} + (1-\beta)\alpha \frac{\partial^2 c}{\partial h_{Lt}\partial x_t}]dx_t - [\beta \frac{\partial^2 c}{\partial h_{Lt}^2} + (1-\beta)\alpha \frac{\partial^2 c}{\partial h_{Lt}^2}]dQ_t \tag{B13}$$

$$+[\beta \frac{\partial^2 c}{\partial h_{It}^2} + (1-\beta)\alpha \frac{\partial^2 c}{\partial h_{It}^2} + \gamma(\beta F''(h_{It}) + G''(h_{It}))]dh_{It} =$$

$$-(\beta F'(h_{It}) + G'(h_{It}))d\gamma - [\beta \frac{\partial^2 c}{\partial h_{It}\partial x_t} + (1-\beta)\alpha \frac{\partial^2 c}{\partial h_{It}\partial x_t}]dx_t - \tag{B14}$$

$$[\beta \frac{\partial^2 c}{\partial h_{It}\partial h_{Lt}} + (1-\beta)\alpha \frac{\partial^2 c}{\partial h_{It}\partial h_{Lt}}]dQ_t$$

dh_{It} is the only variable that enters in (B14) and, therefore, (B14) can be used to characterize the reaction

function.

In (B14) we may set $d\gamma = dx_t = 0$ and reach:

$$\frac{dh_{It}}{dQ_t} = -\frac{(\beta + (1-\beta)\alpha)\frac{\partial^2 c}{\partial h_{It}\partial h_{Lt}}}{(\beta + (1-\beta)\alpha)\frac{\partial^2 c}{\partial h_{It}^2} + \gamma(\beta F''(h_{It}) + G''(h_{It}))} \tag{B15}$$

We have that $0 < \beta < 1$, $0 < \alpha < 1$, $0 < \gamma < 1$, $\dfrac{\partial^2 c}{\partial h_{It}^2} > 0$, $F''(h_{It}) > 0$ and $G''(h_{It}) > 0$ and this imply that the

denominator in (B15) is positive. With respect to the nominator $\dfrac{\partial^2 c}{\partial h_{It} \partial h_{Lt}} > 0$ so the nominator is also positive.

In total, we, therefore, reach the conclusion that $\dfrac{dh_{It}}{dQ_t} < 0$.

Concerning $\dfrac{dh_{It}}{d\gamma}$ we set $dQ_t = dx_t = 0$ in (B14) and arrive at:

$$\frac{dh_{It}}{d\gamma} = -\frac{\beta F'(h_{It}) + G'(h_{It})}{(\beta + (1-\beta)\alpha)\dfrac{\partial^2 c}{\partial h_{It}^2} + \gamma(\beta F''(h_{It}) + G''(h_{It}))} \tag{B16}$$

From (B15) we have that the denominator is positive and, in addition, the nominator in (B16) is positive

because $G'(h_{It}) > 0$ and $F'(h_{It}) > 0$. Therefore, we obtain that $\dfrac{dh_{It}}{d\gamma} < 0$.

Last, by setting $dQ_t = d\gamma = 0$ we reach:

$$\frac{\partial h_{It}}{\partial x_t} = -\frac{(\beta + (1-\beta)\alpha)\dfrac{\partial^2 c}{\partial h_{It} \partial x_t}}{(\beta + (1-\beta)\alpha)\dfrac{\partial^2 c}{\partial h_{It}^2} + \gamma(\beta F''(h_{It}) + G''(h_{It}))} \tag{B17}$$

From above the denominator is positive. In addition, we have that $\dfrac{\partial^2 c}{\partial h_{It} \partial x_t} < 0$ so the nominator is negative. In

total, this implies that $\dfrac{\partial h_{It}}{\partial x_t} > 0$.

B.2. Enforcement costs

The inverted reaction function is:

$$\gamma = \gamma(Q_t, x_t, h_{It}) \tag{B18}$$

From (B18) we get:

$$\frac{\partial \gamma}{\partial Q} dQ_t + \frac{\partial \gamma}{\partial x_t} dx_t + \frac{\partial \gamma}{\partial h_{It}} dh_{It} = 0 \tag{B19}$$

Now $\gamma(e_t)$ is the probability of being detected as a function of enforcement effort and we have:

$$\frac{\partial \gamma}{\partial e_t} > 0 \tag{B20}$$

We invert $\gamma(e_t)$ to get $e_t(\gamma)$ and due to (B20) we obtain:

$$\frac{\partial e_t}{\partial \gamma} = \frac{1}{\dfrac{\partial \gamma}{\partial e_t}} > 0 \tag{B21}$$

$\gamma = \gamma(Q_t, x_t, h_{It})$ can be used in $e_t(\gamma)$ and this gives $e_t = e_t(\gamma(Q_t, x_t, h_{It})) = \alpha(Q_t, x_t, h_{It})$. Now we can find

the sign of $\dfrac{\partial \alpha}{\partial h_{It}}$ by using:

$$\frac{\partial \alpha}{\partial h_{It}} = \frac{\partial e_t}{\partial \gamma} \frac{\partial \gamma}{\partial h_{It}} \tag{B22}$$

From (B21) $\dfrac{\partial e_t}{\partial \gamma} > 0$ and furthermore we have that:

$$\frac{\partial \gamma}{\partial h_{It}} = \frac{1}{\dfrac{\partial h_{It}}{\partial \gamma}} \tag{B23}$$

From (B16) $\dfrac{\partial h_{It}}{\partial \gamma} < 0$ and by using this in (B23) we obtain $\dfrac{\partial \gamma}{\partial h_{It}} < 0$. Now (B22) now imply that $\dfrac{\partial \alpha}{\partial h_{It}} < 0$.

For the sign of $\dfrac{\partial \alpha}{\partial x_t}$ we have:

$$\frac{\partial \alpha}{\partial x_t} = \frac{\partial e_t}{\partial \gamma} \frac{\partial \gamma}{\partial x_t} \tag{B24}$$

In (B21) it was stated that $\dfrac{\partial e_t}{\partial \gamma} > 0$ and using by $dQ_t = 0$ in (B19) it is obtained that:

$$\frac{\partial \gamma}{\partial x_t} = -\frac{\dfrac{\partial h_{It}}{\partial x_t}}{\dfrac{\partial h_{It}}{\partial \gamma}} \tag{B25}$$

From (B17) $\dfrac{\partial h_{It}}{\partial x_t} > 0$, and in (B16) we reached that $\dfrac{\partial h_{It}}{\partial \gamma} < 0$. Combining this in (B25) $\dfrac{\partial \gamma}{\partial x_t} > 0$, which by

using (B24) gives $\dfrac{\partial \alpha}{\partial x_t} > 0$.

Lastly, we turn attention to the sign of $\dfrac{\partial \alpha}{\partial Q_t}$ where we have:

$$\frac{\partial \alpha}{\partial Q_t} = \frac{\partial e_t}{\partial \gamma}\frac{\partial \gamma}{\partial Q_t} \tag{B26}$$

Using $dx_t = 0$ in (B19) and solving for $\dfrac{\partial \gamma}{\partial Q_t}$ we get:

$$\frac{\partial \gamma}{\partial Q_t} = -\frac{\dfrac{\partial h_{It}}{\partial Q_t}}{\dfrac{\partial h_{It}}{\partial \gamma}} \tag{B27}$$

From (B16) $\dfrac{\partial h_{It}}{\partial \gamma} < 0$ and using (B15) implies that $\dfrac{\partial h_{It}}{\partial Q_t} < 0$. Therefore, $\dfrac{\partial \gamma}{\partial Q_t} < 0$ and by using this in (B26) it

follows that $\dfrac{\partial \alpha}{\partial Q_t} < 0$.

Now the enforcement cost function is given as $K(e_t)$ and we assume that:

$$\frac{\partial K}{\partial e_t} > 0 \text{ and } \frac{\partial^2 K}{\partial e_t^2} > 0 \tag{B28}$$

From before $e_t = e_t(\gamma(Q_t, x_t, h_{It})) = \alpha(Q_t, x_t, h_{It})$ and inserting this in the enforcement cost function gives

$K(e_t(\gamma(Q_t, x_t, h_{It}))) = F(\alpha(Q_t, x_t, h_{It})) = E(Q_t, x_t, h_{It})$. Now we can find the sign of the derivatives and we

start by $\dfrac{\partial E}{\partial Q_t}$ where we have:

$$\frac{\partial E}{\partial Q_t} = \frac{\partial F}{\partial \alpha}\frac{\partial \alpha}{\partial Q_t} = \frac{\partial K}{\partial e_t}\frac{\partial e_t}{\partial \gamma}\frac{\partial \gamma}{\partial Q_t} \tag{B29}$$

In (B26) $\dfrac{\partial \alpha}{\partial Q_t} = \dfrac{\partial e_t}{\partial \gamma}\dfrac{\partial \gamma}{\partial Q_t} < 0$ and from (B28) $\dfrac{\partial K}{\partial e_t} > 0$ implying that $\dfrac{\partial E}{\partial Q_t} < 0$.

Next for the sign of $\dfrac{\partial E}{\partial x_t}$ we have that:

$$\frac{\partial E}{\partial x_t} = \frac{\partial F}{\partial \alpha}\frac{\partial \alpha}{\partial x_t} = \frac{\partial K}{\partial e_t}\frac{\partial e_t}{\partial \gamma}\frac{\partial \gamma}{\partial x_t} \tag{B30}$$

Using (B24) we have that $\dfrac{\partial \alpha}{\partial x_t} = \dfrac{\partial e_t}{\partial \gamma}\dfrac{\partial \gamma}{\partial x_t} > 0$ and from (B28) $\dfrac{\partial K}{\partial e_t} > 0$ which implies that $\dfrac{\partial E}{\partial x_t} > 0$.

Last for the sign of $\dfrac{\partial E}{\partial h_{It}}$ we get:

$$\frac{\partial E}{\partial h_{It}} = \frac{\partial F}{\partial \alpha}\frac{\partial \alpha}{\partial h_{It}} = \frac{\partial K}{\partial e_t}\frac{\partial e_t}{\partial \gamma}\frac{\partial \gamma}{\partial h_{It}} \tag{B31}$$

From (B22) $\dfrac{\partial \alpha}{\partial h_{It}} = \dfrac{\partial e_t}{\partial \gamma}\dfrac{\partial \gamma}{\partial h_{It}} < 0$ and using (B28) $\dfrac{\partial K}{\partial e_t} > 0$. In total, this implies that $\dfrac{\partial E}{\partial h_{It}} < 0$.

Appendix C: Share of revenue

C.1. Reaction functions

With the share of revenue rule the wage function is:

$$W\left(h_{Lt}, h_{It}\right) = \beta\left(p_t\left(h_{Lt} + h_{It}\right)\right) \tag{C1}$$

The general first-order conditions for the employee are given by (C1)-(C3) in appendix B.1. Inserting the derivatives of (C1) in the first-order conditions gives:

$$p - \alpha \frac{\partial c}{\partial h_{Lt}} - u_t = 0 \tag{C2}$$

$$p - \alpha \frac{\partial c}{\partial h_{It}} - \gamma G'\left(h_{It}\right) = 0 \tag{C3}$$

$$h_{Lt} = Q_t \tag{C4}$$

By total differentiating (C2) - (C4) we get that:

$$\alpha \frac{\partial^2 c}{\partial h_{Lt}^2} dh_{Lt} + \alpha \frac{\partial^2 c}{\partial h_{Lt} \partial h_{It}} dh_{It} + du_t = -\alpha \frac{\partial^2 c}{\partial h_{Lt} \partial x_t} dx_t \tag{C5}$$

$$\alpha \frac{\partial^2 c}{\partial h_{It} \partial h_{Lt}} dh_{Lt} + [\alpha \frac{\partial^2 c}{\partial h_{It}^2} + \gamma G''(h_{It})] dh_{It} = -\alpha \frac{\partial^2 c}{\partial h_{It} \partial x_t} dx_t - G'(h_{It}) d\gamma \tag{C6}$$

$$dh_{Lt} = dQ_t \tag{C7}$$

(C7) can be inserted into (C5) and (C6) which yields:

$$\alpha \frac{\partial^2 c}{\partial h_{Lt} \partial h_{It}} dh_{It} + du_t = -\alpha \frac{\partial^2 c}{\partial h_{Lt} \partial x_t} dx_t - \alpha \frac{\partial^2 c}{\partial h_{Lt}^2} dQ_t \tag{C8}$$

$$[\alpha \frac{\partial^2 c}{\partial h_{It}^2} + \gamma G''(h_{It})] dh_{It} = -\alpha \frac{\partial^2 c}{\partial h_{It} \partial x_t} dx_t - G'(h_{It}) d\gamma - \alpha \frac{\partial^2 c}{\partial h_{It} \partial h_{Lt}} dQ_t \tag{C9}$$

Since (C9) only depend on dh_{It}, this equation is the one we will consider to derive the properties of the reaction function.

First, we investigate the sign of $\dfrac{\partial h_{It}}{dQ_t}$ and by setting $d\gamma = dx_t = 0$ in (C9) we reach:

$$\frac{\partial h_{It}}{dQ_t} = -\frac{\alpha \dfrac{\partial^2 c}{\partial h_{It} \partial h_{Lt}}}{\alpha \dfrac{\partial^2 c}{\partial h_{It}^2} + \gamma G''(h_{It})} \qquad (C10)$$

Concerning (C10) $0 < \alpha < 1$ $0 < \gamma < 1$ $\alpha \dfrac{\partial^2 c}{\partial h_{It}^2} > 0$ and $G''(h_{It}) > 0$ so the denominator is positive. The nominator is also positive because $\dfrac{\partial^2 c}{\partial h_{It} \partial h_{Lt}} > 0$. In total, (C10) therefore imply that $\dfrac{\partial h_{It}}{dQ_t} < 0$.

Setting $d\gamma = dQ_t = 0$ in (C9) gives:

$$\frac{\partial h_{It}}{dx_t} = -\frac{\alpha \dfrac{\partial^2 c}{\partial h_{It} \partial x_t}}{\alpha \dfrac{\partial^2 c}{\partial h_{It}^2} + \gamma G''(h_{It})} \qquad (C11)$$

As in (C10) the denominator is positive. However, now $\dfrac{\partial^2 c}{\partial h_{It} \partial x_t} < 0$ so the nominator is negative and this imply that $\dfrac{\partial h_{It}}{dx_t} > 0$.

Last, we evaluate the sign of $\dfrac{\partial h_{It}}{d\gamma}$ by setting $dx_t = dQ_t = 0$ in (C9). This gives:

$$\frac{\partial h_{It}}{d\gamma} = -\frac{G'(h_{It})}{\alpha \dfrac{\partial^2 c}{\partial h_{It}^2} + \gamma G''(h_{It})} \qquad (C12)$$

The denominator is positive from (C10) and the nominator is also positive because $G'(h_{It}) > 0$. This implies that $\dfrac{\partial h_{It}}{d\gamma} < 0$.

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C.2. Enforcement costs

As before we have an inverted the reaction function given by:

$$\gamma = \gamma(Q_t, x_t, h_{It})$$ (C13)

(C13) can be total differentiating:

$$\frac{\partial \gamma}{\partial Q} dQ_t + \frac{\partial \gamma}{\partial x_t} dx_t + \frac{\partial \gamma}{\partial h_{It}} dh_{It} = 0$$ (C14)

Now the probability of being detected is defined as $\gamma(e_t)$ and we have that:

$$\frac{\partial \gamma}{\partial e_t} > 0$$ (C15)

From $\gamma(e_t)$ we get $e_t(\gamma)$ and because of (C15) we have that:

$$\frac{\partial e_t}{\partial \gamma} = \frac{1}{\dfrac{\partial \gamma}{\partial e_t}} > 0$$ (C16)

(C13) can be substituted into $e_t(\gamma)$ to obtain $e_t = e_t(\gamma(Q_t, x_t, h_{It})) = \alpha(Q_t, x_t, h_{It})$. Now we want to find the

sign of the derivatives of $\alpha(Q_t, x_t, h_{It})$. First, we consider the sign of $\dfrac{\partial \alpha}{\partial h_{It}}$:

$$\frac{\partial \alpha}{\partial h_{It}} = \frac{\partial e_t}{\partial \gamma} \frac{\partial \gamma}{\partial h_{It}}$$ (C17)

From (C16) it is obtained that $\dfrac{\partial e_t}{\partial \gamma} > 0$. Furthermore, we have:

$$\frac{\partial \gamma}{\partial h_{It}} = \frac{1}{\dfrac{\partial h_{It}}{\partial \gamma}}$$ (C18)

(C12) imply that $\dfrac{\partial h_{It}}{\partial \gamma} < 0$, and therefore we have that $\dfrac{\partial \gamma}{\partial h_{It}} < 0$ by using (C18). Now (C17) implies that

$\dfrac{\partial \alpha}{\partial h_{It}} < 0$ Concerning the sign of $\dfrac{\partial \alpha}{\partial x_t}$ we get that:

$$\frac{\partial \alpha}{\partial x_t} = \frac{\partial e_t}{\partial \gamma} \frac{\partial \gamma}{\partial x_t} \tag{C19}$$

(C16) express that $\dfrac{\partial e_t}{\partial \gamma} > 0$ and by using $dQ_t = 0$ in (C14) we reach:

$$\frac{\partial \gamma}{\partial x_t} = -\frac{\dfrac{\partial h_{It}}{\partial x_t}}{\dfrac{\partial h_{It}}{\partial \gamma}} \tag{C20}$$

In (C11) we have that $\dfrac{\partial h_{It}}{\partial x_t} > 0$, and from (C18) we reached that $\dfrac{\partial h_{It}}{\partial \gamma} < 0$. Combining this information implies

that $\dfrac{\partial \gamma}{\partial x_t} > 0$ and using (C19) gives $\dfrac{\partial \alpha}{\partial x_t} > 0$.

Lastly, we find the sign of $\dfrac{\partial \alpha}{\partial Q_t}$ by using that:

$$\frac{\partial \alpha}{\partial Q_t} = \frac{\partial e_t}{\partial \gamma} \frac{\partial \gamma}{\partial Q_t} \tag{C21}$$

By setting $dx_t = 0$ in (C14) we get:

$$\frac{\partial \gamma}{\partial Q_t} = -\frac{\dfrac{\partial h_{It}}{\partial Q_t}}{\dfrac{\partial h_{It}}{\partial \gamma}} \tag{C22}$$

From (C18) $\dfrac{\partial h_{It}}{\partial \gamma} < 0$ and furthermore we have that $\dfrac{\partial h_{It}}{\partial Q_t} < 0$ in (C10). Therefore, (C22) implies that $\dfrac{\partial \gamma}{\partial Q_t} < 0$

and using this in (C21) gives $\dfrac{\partial \alpha}{\partial Q_t} < 0$.

Now the enforcement cost function is given as $K(e_t)$ and we assume that:

$$\frac{\partial K}{\partial e_t} > 0 \text{ and } \frac{\partial^2 K}{\partial e_t{}^2} > 0 \tag{C23}$$

Now we have that $e_t = e_t(\gamma(Q_t, x_t, h_{It})) = \alpha(Q_t, x_t, h_{It})$ and inserting this in the enforcement cost function

gives $K(e_t(\gamma(Q_t, x_t, h_{It}))) = F(\alpha(Q_t, x_t, h_{It})) = E(Q_t, x_t, h_{It})$. Now we can find the sign of the derivatives

of the enforcement cost function and we start by the sign of $\dfrac{\partial E}{\partial Q_t}$ where we have:

$$\frac{\partial E}{\partial Q_t} = \frac{\partial F}{\partial \alpha}\frac{\partial \alpha}{\partial Q_t} = \frac{\partial K}{\partial e_t}\frac{\partial e_t}{\partial \gamma}\frac{\partial \gamma}{\partial Q_t} \tag{C24}$$

From (C21) we get that $\dfrac{\partial \alpha}{\partial Q_t} = \dfrac{\partial e_t}{\partial \gamma}\dfrac{\partial \gamma}{\partial Q_t} < 0$ and from (C23) $\dfrac{\partial K}{\partial e_t} > 0$ implying that $\dfrac{\partial E}{\partial Q_t} < 0$.

Next for the sign of $\dfrac{\partial E}{\partial x_t}$ we have that:

$$\frac{\partial E}{\partial x_t} = \frac{\partial F}{\partial \alpha}\frac{\partial \alpha}{\partial x_t} = \frac{\partial K}{\partial e_t}\frac{\partial e_t}{\partial \gamma}\frac{\partial \gamma}{\partial x_t} \tag{C25}$$

Using (C19) we have that $\dfrac{\partial \alpha}{\partial x_t} = \dfrac{\partial e_t}{\partial \gamma}\dfrac{\partial \gamma}{\partial x_t} > 0$ and using that $\dfrac{\partial K}{\partial e_t} > 0$ in (C23) this implies that $\dfrac{\partial E}{\partial x_t} > 0$.

Last for $\dfrac{\partial E}{\partial h_{It}}$ we get:

$$\frac{\partial E}{\partial h_{It}} = \frac{\partial F}{\partial \alpha}\frac{\partial \alpha}{\partial h_{It}} = \frac{\partial K}{\partial e_t}\frac{\partial e_t}{\partial \gamma}\frac{\partial \gamma}{\partial h_{It}} \tag{C26}$$

(C17) gives $\dfrac{\partial \alpha}{\partial h_{It}} = \dfrac{\partial e_t}{\partial \gamma}\dfrac{\partial \gamma}{\partial h_{It}} < 0$ and using (C23) we have that $\dfrac{\partial K}{\partial e_t} > 0$. In total, this implies that $\dfrac{\partial E}{\partial h_{It}} < 0$.

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