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## ON AVOIDANCE ACTIVITIES IN FISHERY ENFORCEMENT MODELS

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**ABSTRACT.** Compliance and enforcement in fisheries are important issues from an economic point of view since management measures are useless without a certain level of enforcement. These conclusions come from the well-established theoretical literature on compliance and enforcement problems within fisheries and a common result is that, it is efficient to set fines as high as possible and monitoring as low as possible, when fines are costless and offenders are risk neutral. However, this result is sensitive to the assumption that fishermen cannot engage in avoidance activities, e.g., activities to reduce the likelihood of being detected when noncomplying. The paper presents a model of fisheries that allows the fishermen to engage in avoidance activities. The conclusions from the model are that, under certain circumstances, fines are costly transfers to society since they not only have a direct positive effect on the level of deterrence, but also an indirect negative effect in the form of increased avoidance activities to reduce the probability of detection. The paper contributes to the literature on avoidance activities by introducing the externality from the illegal behavior as an endogenous effect on other offenders. For an externality, that has an exogenous effect on other actors, Malik shows that fines are only costly transfers for conditional deterrence (when one actor is deterred while another actor is not). For fisheries, we show that fines are also costly transfers under no deterrence (when no agents are deterred).

**KEY WORDS:** Bioeconomic modeling, monitoring, enforcement, fines, avoidance, externalities, fisheries.

**1. Introduction.** A well-established result in the compliance and enforcement literature is that it is efficient to set fines as high as possible and monitoring as low as possible when fines are costless and offenders are risk neutral; see, e.g.,

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Polinsky and Shavell [1979]. This is due to the fact that monitoring is costly for society while fines are costless. Therefore, costs are saved by increasing fines and reducing monitoring effort. However, this result may break down if the offenders have the opportunity to engage in activities that reduce the likelihood of being detected and fined (called avoidance activities); see Malik [1990], Langlais [2008], and Friehe [2010] for examples. The reason is that avoidance activities may violate the assumption that fines are costless transfers for society. Malik [1990] demonstrates this conclusion in a model where individuals engage in an activity that creates an external cost for society and shows that it is not necessarily optimal to set fines as high as possible. Deterrence is important in the analysis by Malik [1990] and is defined as the level at which agents are deterred from the illegal activity. In Malik [1990], fines remain costless transfers for society under no deterrence and full deterrence. However, under conditional deterrence where only part of the illegal offences is deterred, fines become costly transfers for society, and it is no longer optimal to set fines for offenses as high as possible. The intuition behind this result is that avoidance is a costly activity and that avoidance activities increase in line with fines. Malik [1990] shows these results in a model with constant marginal costs and an externality, which is exogenous to the group of agents, but internal to society, e.g., it does not arise as a consequence of interaction between agents. Air pollution, which does not influence other firms, is an example of such an exogenous externality. The intuition behind the result in Malik [1990] is that, with constant marginal costs and an exogenous externality, a sort of bang-bang solution arises. Either agents engage fully in illegal activities involving a negative externality or they do not involve in activities causing negative externalities at all. Fisheries provide yet another example of how individuals' choices can result in an externality for society. However, this externality is endogenous to the group of agents (fishermen), since it affects the common resource, i.e., the externality arises as a consequence of interactions between agents.<sup>1</sup> To avoid this externality problem, most fisheries are regulated, but without monitoring and enforcement, the regulation is of no value; see Sutinen and Andersen [1985]. However, the regulation and enforcement of fisheries create an incentive to become involved in avoidance activities.<sup>2</sup> One example of avoidance activities is fishermen who inform other fishermen about inspectors in certain harbors so they can avoid landing in these harbors. A typical fisheries economic model also has increasing marginal costs. Therefore, the assumptions in a fishery economic model differ from the original model by Malik [1990], which has constant marginal costs and an exogenous externality.

A small number of studies have included avoidance effort and costs in a fisheries enforcement model (Anderson and Lee [1986], Milliman [1986], Charles et al. [1999]). These studies investigate optimal management with avoidance costs. Milliman [1986] analyzes the impact of including illegal rents on optimal regulation. Enforcement is assumed to be imperfect because there are both legal and illegal rents. Milliman [1986] explores if illegal rents shall be taken into account

when optimal regulation is fixed. There are large differences in optimal policies depending on whether or not illegal rents are taken into account. When legal rents are maximized, avoidance activities are disregarded. A regulatory instrument that reduces illegal activities without increasing costs shall be selected when total rents are maximized. Anderson and Lee [1986] consider an effort-regulated fishery. Effort above a target level is fined if detected. The profit function of vessels includes the expected fine and avoidance costs apart from revenue and operating costs. The optimal policy is determined by maximizing total gain. With these assumptions, Anderson and Lee [1986] show that the social cost of avoidance is important when optimal management is selected. Charles et al. [1999] consider input and output control under imperfect enforcement. Fishermen maximize the profit, including the expected punishment and avoidance costs. Regarding the choice between input and output control, a general conclusion cannot be reached. It is case specific which control method shall be selected. Our paper differs from Milliman [1986], Anderson and Lee [1986], and Charles et al. [1999]. The above-mentioned literature studies optimal management when including avoidance costs. Our paper analyzes if fines are costly or costless transfers in the light of avoidance.

The paper is organized as follows. In Section 2, a model for individual fisherman behavior is introduced. Section 3 includes the problem of society and studies optimal enforcement. The paper is discussed and concluded in Section 4.

**2. Individual fisherman behavior.** The individual fisherman is a profit-maximizing agent, who gains profits from harvesting either legally or illegally. When harvesting illegally, the fisherman breaks the regulation and there is a possibility that he will be detected and fined. To reduce the likelihood of detection, the fisherman can engage in avoidance activities, which reduce the probability of being detected when engaging in illegal activities. Following Malik [1990], we assume that the probability of being detected,  $\pi$ , is a function of monitoring effort,  $m$ , and avoidance effort,  $a$ . It is assumed that there is full information about  $\pi$ ,  $m$ , and  $a$  for each individual fisherman in the model. Thus, fishermen know the level of monitoring effort. Regarding the probability of being detected, we assume that:

$$(1) \quad \pi(0, a) = 0 \text{ and } \frac{\partial \pi(0, a)}{\partial a} = 0 \text{ for all } a > 0.$$

Thus, without monitoring effort,  $m = 0$ , it is assumed that there is no probability of being detected. In addition, with no monitoring effort there is no change in the probability of being caught as a consequence of changes in avoidance effort. Furthermore, it is assumed that the probability of being caught increases with monitoring effort and decreases with avoidance effort. This corresponds to the following

assumptions regarding the probability of being caught:

$$(2) \quad \begin{aligned} \frac{\partial \pi(m, a)}{\partial m} &> 0, \frac{\partial \pi(m, a)}{\partial a} < 0, \frac{\partial^2 \pi(m, a)}{\partial m^2} < 0, \\ \text{and } \frac{\partial^2 \pi(m, a)}{\partial a^2} &> 0 \text{ for all } a, m > 0. \end{aligned}$$

The second-order conditions imply that the probability of being detected is nonlinear.

The fishermen's illegal activity is aggregated into a single-catch measure called illegal landings.<sup>3</sup> Each individual fisherman chooses how much to land legally ( $h_L$ ) and how much to land illegally ( $h_I$ ) depending on the available individual non-transferable quota,  $\bar{h}$ .<sup>4</sup> We distinguish between legal and illegal landings in order to facilitate the analysis later in the paper. It is, also, assumed that the price for legal and illegal landings is identical.<sup>5</sup> In choosing legal landings, illegal landings and avoidance effort, the fisherman maximizes expected net profit,  $N(h_L, h_I, a)$ , subject to the regulation on legal harvest:

$$(3) \quad \text{Max}_{h_L, h_I, a} N(h_L, h_I, a) = \text{Max}[p(h_L + h_I) - c(h_L, h_I, x) - \pi(m, a)fh_I - d(a, h_I)]$$

s.t

$$(4) \quad h_L \leq \bar{h},$$

where  $N(h_L, h_I, a)$  is the profit from the fishing activity,  $p$  is the output price,  $x$  is the stock size,  $f$  is the fine set by society per unit of illegal harvest,  $c(h_L, h_I, x)$  is the cost function of harvesting with  $\frac{\partial c}{\partial h_I} > 0$ ,  $\frac{\partial c}{\partial h_L} > 0$ , and  $\frac{\partial c}{\partial x} < 0$ , and  $d(a, h_I)$  is the avoidance cost function. It is assumed that  $\frac{\partial d}{\partial h_I} > 0$  and  $\frac{\partial d}{\partial a} > 0$ .

In equation (3), the avoidance costs function is written in the most general way by assuming that it is a function of avoidance effort and illegal landings. Note that the inclusion of  $d(h_I, a)$  makes the analysis different from Malik [1990], where avoidance effort is simply subtracted from the profit function and set equal to avoidance cost. In our paper, avoidance costs are subtracted from the profit function and are a function of avoidance effort. Thus, the assumptions about avoidance activities differ. The costs of harvesting are also formulated in the most general way in this paper by assuming that they are a function of legal landings, illegal landings, and stock size,  $c(h_L, h_I, x)$ .<sup>6</sup> Note that, in addition to the traditional individual fisherman problem where fishermen only decide on legal and illegal harvest, the profit is also maximized with respect to avoidance effort. Thus,  $a$  is an additional choice variable for the fisherman. The profit includes the expected penalty for the individual fisherman,  $\pi(m, a)fh_I$ . In maximizing equation (3), the individual fisherman is subject to an

individual nontransferable quota represented in equation (4). Equation (4) states that legal landings cannot be larger than the quota.<sup>7</sup> Harvest above the quota is illegal harvest. We assume that fishermen disregard consequences of harvest on the fish stock when maximizing expected profit. Thus, the fishermen are myopic and disregard the resource constraint when determining their harvest.<sup>8</sup>

As mentioned above, we assume that the price of legal and illegal landings is the same. By also assuming that the marginal costs of illegal landings are higher than the marginal costs of legal landings, we can conclude that the marginal profit for legal landings is higher than the marginal profit for illegal landings for all  $h_L$  and  $h_I$ .<sup>9</sup> This implies that fishermen only engage in illegal landings after reaching the quota limit. Since the interesting aspect of the paper includes modeling avoidance effort in relation to illegal landings, the quota restriction in equation (4) is assumed to be binding.<sup>10</sup> Thus, the quota restriction may be substituted into the objective function and the fishermen's maximization problem may be written as:

$$(5) \quad \text{Max}_{h_I, a} N(h_I, a) = \text{Max}[p(\bar{h} + h_I) - c(\bar{h}, h_I, x) - \pi(m, a)f h_I - d(a, h_I)].$$

With respect to equation (5),  $h_L = \bar{h}$  implies that legal landings are no longer a control variable. Therefore, the maximization in equation (5) only occurs with respect to  $h_I$  and  $a$ . Thus, the fishermen do not take into account the effect they have on other fishermen, and the endogenous externality problem arises as a consequence of interactions between agents.

The first-order conditions of equation (5) are:

$$(6) \quad p - \frac{\partial c(\bar{h}, h_I, x)}{\partial h_I} - \pi(m, a)f - \frac{\partial d}{\partial h_I} = 0,$$

$$(7) \quad -\frac{\partial \pi(m, a)}{\partial a} f h_I - \frac{\partial d}{\partial a} = 0.$$

With a nonlinear expected probability function, as assumed in equation (2), we reach an interior solution in equations (6) and (7). In equation (6), the marginal revenue of illegal landings ( $p$ ) equals the expected marginal costs, which are composed of the marginal production costs ( $\frac{\partial c}{\partial h_I}$ ), the expected marginal fine costs ( $\pi(m, a)f$ ), and the marginal avoidance costs ( $\frac{\partial d}{\partial h_I}$ ). Equation (7) expresses that the marginal benefits of avoidance effort (a reduction in the expected fine to pay,  $\frac{\partial \pi}{\partial a} f h_I$ ) equal the marginal cost of avoidance effort ( $\frac{\partial d}{\partial a}$ ).<sup>11</sup> Based on equations (6) and (7), the optimal response of landings and avoidance effort may be found for each level of monitoring effort and fine. These could be expressed as  $h_I(m, f)$  and  $a(m, f)$ , which capture the fishermen's response functions. To describe the properties of these responses requires specific forms for the included functions. The important

message is, however, that there is an interaction between the decided level of avoidance effort, illegal landing, the monitoring effort, and the fine set by society. For the analysis in Section 3, it is convenient to have information about the sign of  $\frac{\partial a}{\partial f}$ . In the Appendix, it is shown that:

$$(8) \quad \frac{da}{df} = \frac{\left( \frac{\partial^2 N}{\partial a \partial f} \frac{\partial^2 N}{\partial h_I^2} - \frac{\partial^2 N}{\partial h_I \partial f} \frac{\partial^2 N}{\partial h_I \partial a} \right)}{\frac{\partial^2 N}{\partial h_I^2} \frac{\partial^2 N}{\partial a^2} - \frac{\partial^2 N}{\partial h_I \partial a} \frac{\partial^2 N}{\partial h_I \partial a}}.$$

It seems reasonable to assume that the direct effects ( $\frac{\partial^2 N}{\partial h_I^2}$  and  $\frac{\partial^2 N}{\partial a^2}$ ) dominates the indirect effect ( $\frac{\partial^2 N}{\partial a \partial f}$ ,  $\frac{\partial^2 N}{\partial h_I \partial f}$  and  $\frac{\partial^2 N}{\partial h_I \partial a}$ ). Therefore,  $\frac{\partial^2 N}{\partial a \partial f} \frac{\partial^2 N}{\partial h_I^2} > \frac{\partial^2 N}{\partial h_I \partial f} \frac{\partial^2 N}{\partial h_I \partial a}$  and  $\frac{\partial^2 N}{\partial h_I^2} \frac{\partial^2 N}{\partial a^2} > \frac{\partial^2 N}{\partial h_I \partial a} \frac{\partial^2 N}{\partial h_I \partial a}$ . with this assumption,  $\frac{da}{df} > 0$ .

In the Appendix, we also arrive at a condition using actual functional forms for  $N$ . This is also calculated in the Appendix and if  $h_I$  is large, the limits are given as:

$$(9) \quad h_I > \frac{\pi(m, a) \frac{\partial \pi(m, a)}{\partial a} \left( f + \frac{\partial^2 d(h_I, a)}{\partial h_I \partial a} \right)}{\frac{\partial \pi(m, a)}{\partial a} \left( \frac{\partial^2 c(\bar{h}, h_I, x)}{\partial h_I^2} + \frac{\partial^2 d(h_I, a)}{\partial h_I^2} \right)},$$

$$(10) \quad h_I > \frac{\left( \frac{\partial^2 c(\bar{h}, h_I, x)}{\partial h_I^2} + \frac{\partial^2 d(h_I, a)}{\partial h_I^2} \right) + \pi(m, a) \frac{\partial \pi(m, a)}{\partial a} \left( f + \frac{\partial^2 d(h_I, a)}{\partial h_I \partial a} \right)}{\left( \frac{\partial^2 c(\bar{h}, h_I, x)}{\partial h_I^2} + \frac{\partial^2 d(h_I, a)}{\partial h_I^2} \right) \left( \frac{\partial^2 \pi}{\partial a^2} \right) f}.$$

We assume that (9) and (10) are fulfilled so that  $\frac{da}{df} > 0$ . This seems reasonable because  $\pi(m, a)$  dominates the first- and second-order effect ( $\frac{\partial \pi(m, a)}{\partial a}$  and  $\frac{\partial^2 \pi}{\partial a^2}$ ). This result is intuitively clear since higher fines would increase the incentive to avoid paying them, e.g., increase avoidance activities.

For what follows, it is useful to define the marginal revenue and the marginal costs of illegal landings, as  $MR_I$  and  $MC_I$ , from equation (6):

$$(11) \quad MR_I = p,$$

$$(12) \quad MC_I = \frac{\partial c}{\partial h_I} + \pi(m, a)f + \frac{\partial d}{\partial h_I}.$$

Based on the marginal principle, the fisherman continues to fish illegally if  $MR_I > MC_I$ , and restricts illegal fishery if  $MR_I < MC_I$ . The maximum principle states that  $MR_I = MC_I$ . This is also seen in the optimality condition in (6).

**3. Optimal enforcement.** The social optimal level of enforcement is determined by maximizing the objective function,  $W$ . Following the discussion by Milliman [1986], the welfare for society is the total surplus, including the illegal surplus. It can be discussed whether the rents from illegal activities should be included in the social welfare function or not. In the presented model, illegal rents are part of the surplus generated by fisheries and are thus included.

Basic enforcement theory concludes that it is never optimal to enforce regulations such that all illegal activities are prevented, see, e.g., Becker [1968] and Stigler [1971]. This conclusion is questioned in the present model. Society faces a problem of finding the level of deterrence among heterogeneous fishermen. For modeling purposes, it is assumed that fishermen can be categorized into different groups. These groups are assumed to differ from each other depending on their harvesting costs. The groups could be formed based on gear type, vessel type, or skipper's skill. Obviously, these groups are also distinguished by the employed level of avoidance (measured by the avoidance cost function), which is assumed unknown to society. Like Malik [1990] and Milliman [1986], fishermen are classified in two different groups, referred to as type A and type B.<sup>12</sup> Let type B be the groups of fishermen with the lowest marginal harvesting costs for all legal and illegal landings. With this knowledge and the assumption about identical prices, the marginal profit for type B is higher than the marginal profit for type A. In the model, there is asymmetric information since society lacks information about if a fisherman belongs to type A or B and it is not possible to reveal the private information. Thus, screening is not possible. The information available to society is the probability for a fisherman being type A,  $1 - \theta$  and a probability of being type B,  $\theta$ . To solve the information problem, society must implement an enforcement policy (probability of being detected and the fine). Define the dummy parameter,  $\delta^i$ , for each of the types,  $i = A, B$ , to measure if a fisherman engage in illegal fishing or not. With  $\delta^i = 1$ , the individual fisherman of type  $i$  harvests illegally, while fisherman  $i$  does not engage in illegal activity if  $\delta^i = 0$ . It is worth noting that it is assumed that the total quota is always used. This also holds in the case of no illegal activity. With these assumptions, the maximization problem for society is:<sup>13</sup>

$$\begin{aligned}
 \text{Max}_{m, f^A, f^B} W = & (1 - \theta) [ (p(\delta^A h_I^A + h_L^A) - c^A(\delta^A h_I^A, h_L^A, x) - d^A(\delta^A h_I^A, a^A)) ] + \\
 (13) \quad & \theta [ (p(\delta^B h_I^B + h_L^B) - c^B(\delta^B h_I^B, h_L^B, x) - d^B(\delta^B h_I^B, a^B)) ] - e(m),
 \end{aligned}$$



s.t

$$(14) \quad 0 = G(x) - (1 - \theta)(\delta^A h_I^A + h_L^A) - \theta(\delta^B h_I^B + h_L^B),$$

$$(15) \quad f^i \leq q + N^i(h_L^i, \delta^i h_I^i, a^i) \quad \text{for } i = A, B,$$

where  $G(x)$  is the natural growth function of the stock,  $x$ ,  $q$  are an exogenously given level of the wealth for the individual fisherman, and  $e(m)$  is monitoring cost as a function of monitoring effort. It is assumed that  $e'(m) > 0$  and  $e''(m) > 0$ . In the model, we distinguish between monitoring costs ( $e(m)$ ) and monitoring effort ( $m$ ). This makes the analysis in the present paper more general than the one presented in Malik [1990], who assumes monitoring effort and monitoring costs are identical.

Equation (13) is the total welfare function for society depending on the welfare of the individual fisherman. It is the long-run steady-state profit, which is maximized,<sup>14</sup> implying that discounting is excluded. This objective function is maximized with the level of monitoring and size of fines ( $m$  and  $f^i$  for  $i = 1, 2$ ) as control variables. In principle, the quota is also a control variable.<sup>15</sup> However, the first-order condition for the quota does not change the fundamental result of the paper and is, therefore, not included. Equation (14) is the resource restriction implying steady-state use of the resource. This is captured by the condition that the natural growth is equal to the expected harvest. Equation (14) is what distinguishes the fishermen's myopic maximization problem from society's steady-state maximization problem. It could be argued that, because the model is static, the total stock is given and the natural growth is zero. However, equation (14) is useful because the nature of the externality problem becomes clear. Note that the stock size is state variable and that equation (14) is formulated in terms of expected harvest, which is necessary because equations (13)–(15) is an *ex ante* decision problem. Equation (15) states that the fine can never be larger than the exogenous wealth plus the profit. Note that we assume that fines are determined in two levels. Thus, there is one fine for each of the groups, A and B. This is also reflected in the objective function (equation 13) because the maximization occurs with respect to  $f^A$  and  $f^B$ . The problem with fines in two levels is that societies do not know the type of fishermen *ex ante*. However, by assuming that the society can reveal the type of fishermen when the agent is detected, we can abstract from this problem in the following analysis. In what follows we distinguish between a response function for type A and B. Thus, the response function from (6) and (7) is written as  $h_I^A(m, f^A)$ ,  $h_I^B(m, f^B)$ ,  $a^A(m, f^A)$ , and  $a^B(m, f^B)$ . This is done because we operate with fines determined at two levels.

Substituting the response functions into equations (13)–(15) yields:

$$(16) \quad \begin{aligned} \text{Max} W = & (1 - \theta) [p(\delta^A h_I^A(m, f^A) + h_L^A) - c^A(\delta^A h_I^A(m, f^A), h_L^A, x) - \\ & m, f^A, f^B \\ & d^A(a^A(m, f^A), \delta^A h_I^A(m, f^A))] + \theta [p(\delta^B h_I^B(m, f^B) + h_L^B) - \\ & c^B(\delta^B h_I^B(m, f^B), h_L^B, x) - d^B(a^B(m, f^B), \delta^B h_I^B(m, f^B))] - e(m), \end{aligned}$$

s.t.

$$(17) \quad 0 = G(x) - (1 - \theta)(\delta^A h_I^A(m, f^A) + h_L^A) - \theta(\delta^B h_I^B(m, f^B) + h_L^B),$$

$$(18) \quad f^i \leq q + N^i(h_L, \delta^i h_I^i(m, f^i), a^i(m, f^i)) \quad i = A, B.$$

The fishermen will base their decision on whether or not to engage in illegal activities depending on the net profit from illegal landings. Thus, the fishermen determine  $\delta^i$  based on:

$$(19) \quad \delta^i = \begin{cases} 0 & \text{if } MR_I^i \leq MC_I^i \text{ for all } h_I^i \\ 1 & \text{if } MR_I^i > MC_I^i \text{ for some } h_I^i \end{cases},$$

where  $h_I^i$  is the level of illegal harvest. Thus, if  $\delta^i = 0$ , the net profit from illegal harvest is negative and there is no incentive to engage in illegal activities. If there is an incentive to harvest illegally for some  $h_I^i$ ,  $i = 1, 2$ , then  $\delta^i = 1$ .

Society faces a decision about the level of deterrence between the two types of fisherman (does it prefer to deter both groups from illegal harvest, just one group, or none of the groups). To find the solutions to this problem, all four combinations of values of  $\delta^A$  and  $\delta^B$  are investigated. The combination where type A lands illegally and type B lands legally ( $\delta^A = 1$  and  $\delta^B = 0$ ) can be immediately excluded from the analysis since it would imply that the profit for type A is higher than the profit for type B, which, with constant prices and type B being the low cost group, is not a possible scenario. Therefore, if type A lands illegally, so must type B, and  $\delta^A = 1$  and  $\delta^B = 0$  cannot represent a consistent case and, therefore, it is not discussed any further in the subsequent section. Following this, society has three different choices for deterrence:

- (i)  $\delta^A = \delta^B = 0$ , both types are deterred from illegal activities, called *complete deterrence*. None of the groups lands illegally and  $MC_I^B > MR_I^B$ .
- (ii)  $\delta^A = \delta^B = 1$ , none of the types are deterred from illegal activities, labeled *no deterrence*. Both groups land illegally, implying  $MR_I^A \geq MC_I^A$  for some  $h_j$ .
- (iii)  $\delta^A = 0$  and  $\delta^B = 1$ , type A is deterred from illegal activities and type B is not. This possibility is called *conditional deterrence*. Low-cost type (type B) lands

illegally while high-cost type (type A) does not, implying  $MR_I^A < MC_I^A$  and  $MR_I^B > MC_I^B$ .

These three choices for the level of deterrence, determined by society, are analyzed separately in the following subsections to illustrate monitoring and fines.

**3.1. Complete deterrence.** If complete deterrence is used, then the social welfare function in equation (16) is maximized with  $\delta^A = \delta^B = 0$ . An additional restriction is included, to ensure the absence of illegal landings (equation 23 below). In addition, the resource restriction and the restriction on the maximum fine is part of the optimization problem. Note that the condition on maximum fine implies that fines are determined in two levels because they vary between A and B. Note, also, that avoidance costs are zero in the maximization problem. This arises because complete deterrence implies no illegal landings. With the absence of illegal landings there is no avoidance effort. The optimization problem then becomes:

$$(20) \quad \begin{aligned} \text{Max} W = & (1 - \theta)(ph_L^A - c^A(h_L^A, x)) + \theta(ph_L^B - c^B(h_L^B, x)) - e(m), \\ & m, f^A, f^B \end{aligned}$$

s.t.

$$(21) \quad 0 = G(x) - (1 - \theta)h_L^A - \theta h_L^B,$$

$$(22) \quad f^i \leq q + N^i(h_L^i) \quad \text{for } i = A, B,$$

$$(23) \quad MR_I^B \leq MC_I^B.$$

Note that it is desirable for society to set monitoring effort as low as possible and fines at a maximum level, recognizing that both type A and B have the potential to invest in avoidance effort. In addition, the fine depends on whether the agent is type A and type B and, therefore, the fine depends on  $i$ . Formally, the social optimal solution is given by:<sup>16</sup>

$$(24) \quad f^i = q + N^i(h_L^i) \quad \text{for } i = A, B,$$

$$(25) \quad MR_I^A = MC_I^A.$$

Equation (24) expresses that it is desirable to lower monitoring effort,  $m$ , exactly until the point where equation (24) is binding. Thus, it is still optimal to set

monitoring effort as low as possible and fines to the maximum level under complete deterrence since complete deterrence implies no illegal landings.

**3.2. No deterrence.** Under no deterrence, the optimization for society is determined from  $\delta^A = \delta^B = 1$ . Thus, society's maximization problem is:

$$(26) \quad \begin{aligned} \text{Max} W = & (1 - \theta)[p(h_I^A(m, f^A) + h_L^A) - c^A(h_I^A(m, f^A), h_L^A, x) - \\ & m, f^A, f^B \\ & d^A(a^A(m, f^A), h_I^A(m, f^A))] + \theta[p(h_I^B(m, f^B) + h_L^B) - \\ & c^B(h_I^B(m, f^B), h_L^B, x) - d^B(a^B(m, f^B), h_I^B(m, f^B))] - e(m), \end{aligned}$$

s.t.

$$(27) \quad 0 = G(x) - (1 - \theta)(h_I^A(m, f^A) + h_L^A) - \theta(h_I^B(m, f^B) + h_L^B),$$

$$(28) \quad f^i \leq q + N^i(h_L^i, h_I^i(m, f^i), a^i(m, f^i)) \quad \text{for } i = A, B,$$

$$(29) \quad MR_I^A \geq MC_I^A \quad \text{for some } h_I^A.$$

The Lagrange function, assuming that equations (28) and (29) are nonbinding, is:<sup>17</sup>

$$(30) \quad \begin{aligned} L = & (1 - \theta)[p(h_I^A(m, f^A) + h_L^A) - c^A(h_I^A(m, f^A), h_L^A, x) \\ & - d(a^A(m, f^A), h_I^A(m, f^A))] + \theta[p(h_I^B(m, f^B) + h_L^B) \\ & - c^B(h_I^B(m, f^B), h_L^B, x) - d(a^B(m, f^B), h_I^B(m, f^B))] - e(m) \\ & + \lambda(G(x) - (1 - \theta)(h_I^A(m, f^A) + h_L^A) - \theta(h_I^B(m, f^B) + h_L^B)). \end{aligned}$$

The first-order conditions are:

$$(31) \quad \begin{aligned} \frac{\partial L}{\partial m} = & (1 - \theta) \left( p \frac{\partial h_I^A}{\partial m} - \frac{\partial c^A}{\partial h_I^A} \frac{\partial h_I^A}{\partial m} - \frac{\partial d^A}{\partial a^A} \frac{\partial a^A}{\partial m} - \frac{\partial d^A}{\partial h_I^A} \frac{\partial h_I^A}{\partial m} \right) \\ & + \theta \left( p \frac{\partial h_I^B}{\partial m} - \frac{\partial c^B}{\partial h_I^B} \frac{\partial h_I^B}{\partial m} - \frac{\partial d^B}{\partial a^B} \frac{\partial a^B}{\partial m} - \frac{\partial d^B}{\partial h_I^B} \frac{\partial h_I^B}{\partial m} \right) - e'(m) \\ & - \lambda((1 - \theta) \frac{\partial h_I^A}{\partial m} - \theta \frac{\partial h_I^B}{\partial m}) = 0, \end{aligned}$$

$$(32) \quad \frac{\partial L}{\partial f^A} = (1 - \theta) \left( p \frac{\partial h_I^A}{\partial f^A} - \frac{\partial c^A}{\partial h_I^A} \frac{\partial h_I^A}{\partial f^A} - \frac{\partial d^A}{\partial a^A} \frac{\partial a^A}{\partial f^A} - \frac{\partial d^A}{\partial h_I^A} \frac{\partial h_I^A}{\partial f^A} \right) - \lambda(1 - \theta) \frac{\partial h_I^A}{\partial f^A} = 0,$$

$$(33) \quad \frac{\partial L}{\partial f^B} = \theta \left( p \frac{\partial h_I^B}{\partial f^B} - \frac{\partial c^B}{\partial h_I^B} \frac{\partial h_I^B}{\partial f^B} - \frac{\partial d^B}{\partial a^B} \frac{\partial a^B}{\partial f^B} - \frac{\partial d^B}{\partial h_I^B} \frac{\partial h_I^B}{\partial f^B} \right) - \theta \lambda \frac{\partial h_I^B}{\partial f^B} = 0.$$

An implication of the Appendix is that the two derivatives,  $\frac{\partial a^A}{\partial f^A}$  and  $\frac{\partial a^B}{\partial f^B}$ , can be assumed to be positive. This result, and the fact that avoidance effort is included in the objective function, implies that fines are costly transfers with a marginal social value. Increasing fines imply that avoidance effort will increase, which makes monitoring less effective. Therefore, it is no longer optimal to set fines as high as possible and monitoring as low as possible. The solution becomes a trade-off between the benefits of raising  $m$  and  $f^i$  for  $i = 1, 2$ , and the negative spillover effects in the form of increased avoidance activities. This is in opposition to the traditional literature without avoidance effort, which reaches the conclusion that it is optimal to have minimum monitoring and fines are as high as possible. Malik [1990] argues that  $m = 0$ , if there is no deterrence for any level of  $m$  and that there is no reason to monitor and, therefore, no reason to incur avoidance costs. The result that  $m = 0$  and avoidance cost is absent is due to the fact that Malik [1990] has constant marginal costs and an exogenous externality. In this paper, we assume increasing marginal costs and endogenous externalities and show that, with these assumptions, fines become costly transfers. The main reason for the difference in our results and the results in Malik [1990] is that he has a bang-bang solution because costs are constant and the externality is exogenous. Thus, the agents engage in an illegal activity and do that to maximum extent, or they do not engage in an illegal activity. Due to the fact that costs are increasing and the externality is endogenous in this paper, we have a two-stage decision problem, where the agent first decides to engage in an illegal activity and, second, to which extent the illegal activity occurs.<sup>18</sup> Thus, the level of illegal activity is then determined by  $m$  and  $f^i$  for  $i = 1, 2$ .<sup>19</sup>

**3.3. Conditional deterrence.** Finally, the solution with conditional deterrence is analyzed. Under conditional deterrence,  $\delta^A = 0$  and  $\delta^B = 1$ , which implies additional conditions (in equations 36-39. Here, type A individuals are deterred from illegal fishery, but type B individuals are not. Since  $\delta^A = 0$ ,  $a^A(m, f) = 0$ ,

the maximization problem may be written as:

$$(34) \quad \begin{aligned} \text{Max} W = & (1 - \theta)(ph_L^A - c^A(h_L^A, x)) + \theta[p(h_I^B(m, f^B) + h_L^B) - \\ & c^B(h_I^B(m, f^B), h_L^B, x) - d^B(a^B(m, f^B), h_I^B(m, f^B))] - e(m), \end{aligned}$$

s.t.

$$(35) \quad 0 = G(x) - (1 - \theta)h_L^A - \theta(h_I^B(m, f^B) + h_L^B),$$

$$(36) \quad f^A \leq q + N^A(h_L^A),$$

$$(37) \quad f^B \leq q + N^B(h_L^B, h_I^B(m, f^B), a^B(m, f^B)),$$

$$(38) \quad MR_I^A \leq MC_I^A \quad \text{for all } h_I,$$

$$(39) \quad MR_I^B \geq MC_I^B \quad \text{for some } h_I.$$

The Lagrange function with nonbinding equations (36)–(39) is:

$$(40) \quad \begin{aligned} L = & (1 - \theta)(ph_L^A - c^A(h_L^A, x)) + \theta[p(h_I^B(m, f^B) + h_L^B) \\ & - c^B(h_I^B(m, f^B), h_L^B, x) - d^B(a^B(m, f^B), h_I^B(m, f^B))] \\ & - e(m)) + \lambda(G(x) - (1 - \theta)h_L^A - \theta(h_I^B(m, f^B) + h_L^B)). \end{aligned}$$

The first-order conditions based on the partial derivative of equation (40) are:

$$(41) \quad \frac{\partial L}{\partial f^B} = \theta \left( p \frac{\partial h_I^B}{\partial f^B} - \frac{\partial c^B}{\partial h_I^B} \frac{\partial h_I^B}{\partial f^B} - \frac{\partial d^B}{\partial a^B} \frac{\partial a^B}{\partial f^B} - \frac{\partial d^B}{\partial h_I^B} \frac{\partial h_I^B}{\partial f^B} \right) - \lambda \left( \theta \frac{\partial h_I^B}{\partial f^B} \right) = 0,$$

$$(42) \quad \frac{\partial L}{\partial m} = \theta \left( p \frac{\partial h_I^B}{\partial m} - \frac{\partial c^B}{\partial h_I^B} \frac{\partial h_I^B}{\partial m} - \frac{\partial d^B}{\partial a^B} \frac{\partial a^B}{\partial m} - \frac{\partial d^B}{\partial h_I^B} \frac{\partial h_I^B}{\partial m} \right) - e'(m) - \lambda \left( \theta \frac{\partial h_I^B}{\partial m} \right) = 0.$$

As in Section 3.2,  $\frac{\partial a^B}{\partial f} > 0$  and the avoidance costs and effort are included in the objective function. Thus, as for no deterrence, fines become costly transfers and it is no longer optimal to set the fine as high as possible and monitoring as low as possible, because of a spillover effect in the form of increased avoidance activities. The intuition for fines to become costly transfers when avoidance effort is present is that increasing fines increase costly avoidance in order to decrease the probability of being detected. This may in turn increase necessary monitoring effort but that is only a second-order effect. For conditional deterrence, this result is similar to the results reached in Malik [1990]. Thus, the results by Malik [1990] for conditional deterrence also hold in fishery enforcement despite the fact that the models differ. Costs are increasing and the externality is endogenous when the model is applied to fishery management. Again, the main difference between our paper and Malik [1990] is that the terms  $\lambda(\theta \frac{\partial h^B}{\partial f})$  and  $\lambda(\theta \frac{\partial h^B}{\partial m})$  are included.

**4. Conclusion.** A common result in the enforcement literature is that it is optimal to set fines as high as possible and monitoring as low as possible. This result arises because fines are costless transfers while monitoring is costly for society. However, Malik [1990] has shown that if offenders engage in activities to decrease the probability of being detected, this result may not hold. With avoidance activities, fines may no longer be costless transfers for society since they imply a spillover effect of increased avoidance activity and, thereby, they become costly. Malik [1990] demonstrates that this result holds when there is conditional deterrence among groups of offenders, but does not hold when there is full deterrence or no deterrence among the groups of offenders. In reaching this result, Malik [1990] assumes constant marginal costs and an externality, which is exogenous to the offenders. In fisheries, increasing marginal costs are common and the externality is endogenous (the behavior of one offender affects the availability of the stock for other agents or potential offenders). Therefore, the original model must be modified to make it applicable to monitoring and enforcement in fisheries. This paper shows that under both conditional deterrence and no deterrence, fines are costly transfers because of the spillover effects they have on avoidance activities. Thus, the results in a fisheries economic enforcement model with avoidance activities differ from Malik [1990] because no deterrence also implies that fines are costly transfers. The difference in results arises due to variations in model assumptions. Thus, the present model gives a general contribution to the literature by modifying the fishery enforcement model so that it also includes the possibility of fishermen engaging in avoidance activities. The analysis in this paper is based on two major assumptions. First, an absence of discounting by maximizing long-run economic yield is assumed. Second, adjustments toward equilibrium are excluded by restricting the analysis to steady-state equilibrium. Even though intuition suggests that the results are robust to changes in the assumptions, studies of avoidance under discounting and adjustments toward equilibrium are important areas for future research.

## ENDNOTES

1. Even though the fishermen behave myopically by not considering the resource restriction under open access, they are still affected by the other agents' behavior through the resource constraint.

2. See Leon [1994] for empirical evidence.

3. In addition to illegal landings, high grading and by-catches are illegal activities in fisheries. The model in this paper could be extended to include these activities. High grading would require a vintage model (Beverton–Holt model) while by-catches make it necessary to use a multispecies model.

4. Instead of an individual nontransferable quota system, we could have an individual transferable quota (ITQ) system. This would not affect the conclusions in the paper. In an ITQ system, there are still illegal landings if the quota price is high enough, even though the balance of illegal activities would depend on the marginal quota price and the marginal cost of avoidance activities. Consequently, there is an incentive to engage in avoidance activities.

5. The price for illegal landings may be lower than the price for legal landings. This would not change the fundamental conclusions in the paper.

6. An alternative way of defining the cost function would be to assume that costs depend on the sum of  $h_L$  and  $h_I$  ( $c(h_L + h_I, x)$ ). This would, however, be a more specific formulation, is also included in the presented general formulation.

7. An alternative would be to formulate the quota restriction as  $h_I = h_T - \bar{h}$ , where  $h_T$  is the total harvest. However, this is only a matter of notation. Both with the notation in the paper and with the alternative formulation, profit becomes a function of the illegal landings,  $h_I$ .

8. See Clark [1980] for an original contribution and Clark [1990] for an overview.

9. With identical prices for legal and illegal landings, a sufficient (but unnecessary) condition for the marginal profit for legal to be higher than the marginal profit for illegal landings, is that the marginal costs of illegal landings are higher than the marginal costs of legal landings. Note that if the price for legal landings is higher than the price for illegal landings, the marginal profit for legal landings is still higher than the marginal profit for illegal landings.

10. The assumptions that fishermen only land illegally after the quota limit is reached and that the quota restriction is binding are useful. With these assumptions, it is not necessary to derive a first-order condition for legal landings.

11. Note that with (6) and (7), illegal landings become an implicit function of avoidance effort. Thus, we may state that  $h_I(a)$ .

12. It is straightforward to generalize the results to continuous heterogeneity among fishermen.

13. In the private optimization problem,  $h_L = \bar{h}$ . Thus, the quota is exogenously given. In (13)–(15),  $h_L$  is an endogenous variable because it is the maximization for society we describe.

14. Long-run steady-state profit is maximized because it is the objective function for society. This result holds despite the fact that fishermen act myopic. Thus, even though fishermen disregard the fish stock, society can maximize profit.

15. Note that when formulating the quota restriction as  $h_I = h_T - \bar{h}$ , the quota is not a control variable. However, it is intuitively clear to use the formulation in (13) because the quota is policy variable.

16. As a reviewer noted, equation (25) cannot hold at the same time for A and B, since this would imply the marginal revenues for A and B are identical and equal to the price, but marginal costs are higher for type A than for type B. The implications of this is that, if equation (25) should hold for B, it cannot hold for A because the marginal revenue for type A is lower than marginal costs. Thus, equation (25) is formulated for A and in optimum marginal revenue for B is larger than marginal costs.



17. Formally, one has to use Kuhn–Tucker conditions to maximize the problem. However, assuming (25) and (26) is nonbinding simplifies the problem and we can use a Lagrange function.

18. We are grateful to an anonymous referee, who carefully drew our attention to Malik’s bang–bang approach versus our two-stage approach. This helped us to improve the presentation of our results significantly.

19. It could be argued that the fishermen are deterred but not so much that all fishermen drop illegal activity completely. Therefore, comparing this solution to the no-deterrence case of Malik [1990] is not completely valid. If  $m$  would not affect the level of illegal fishing, we are back to solution in Malik [1990].

20. It could, of course, also be fulfilled by the numerator and the denominator being negative, simultaneously.

## APPENDIX

Call the profit function  $N$ . Now the first-order condition is:

$$(A1) \quad \frac{\partial N}{\partial h_I} = 0,$$

$$(A2) \quad \frac{\partial N}{\partial a} = 0.$$

Total differentiation of equations (A1) and (A2) gives:

$$(A3) \quad \frac{\partial^2 N}{\partial h_I^2} dh_I + \frac{\partial^2 N}{\partial h_I \partial a} da + \frac{\partial^2 N}{\partial h_I \partial f} df = 0,$$

$$(A4) \quad \frac{\partial^2 N}{\partial h_I \partial a} dh_I + \frac{\partial^2 N}{\partial a^2} da + \frac{\partial^2 N}{\partial a \partial f} df = 0.$$

Solving equation (A4) for  $dh_i$  gives:

$$(A5) \quad dh_I = - \frac{\left( \frac{\partial^2 N}{\partial a^2} da + \frac{\partial^2 N}{\partial a \partial f} df \right)}{\frac{\partial^2 N}{\partial h_I \partial a}}.$$

Inserting equation (A5) into equation (A3) gives:

$$(A6) \quad -\frac{\frac{\partial^2 N}{\partial h_I^2} \frac{\partial^2 N}{\partial a^2}}{\frac{\partial^2 N}{\partial h_I \partial a}} da + \frac{\frac{\partial^2 N}{\partial h_I \partial a}}{\frac{\partial^2 N}{\partial h_I \partial a}} da - \frac{\frac{\partial^2 N}{\partial a \partial f} \frac{\partial^2 N}{\partial h_I^2}}{\frac{\partial^2 N}{\partial h_I \partial a}} df + \frac{\frac{\partial^2 N}{\partial h_I \partial f}}{\frac{\partial^2 N}{\partial h_I \partial a}} df = 0.$$

Equation (A6) may be written as:

$$(A7) \quad -\frac{\frac{\partial^2 N}{\partial h_I^2} \frac{\partial^2 N}{\partial a^2}}{\frac{\partial^2 N}{\partial h_I \partial a}} da + \frac{\frac{\partial^2 N}{\partial h_I \partial a} \frac{\partial^2 N}{\partial h_I \partial a}}{\frac{\partial^2 N}{\partial h_I \partial a}} da - \frac{\frac{\partial^2 N}{\partial a \partial f} \frac{\partial^2 N}{\partial h_I^2}}{\frac{\partial^2 N}{\partial h_I \partial a}} df + \frac{\frac{\partial^2 N}{\partial h_I \partial f} \frac{\partial^2 N}{\partial h_I \partial a}}{\frac{\partial^2 N}{\partial h_I \partial a}} df = 0.$$

Rewriting equation (A7) gives:

$$(A8) \quad \frac{da}{df} = \frac{\left( \frac{\frac{\partial^2 N}{\partial a \partial f} \frac{\partial^2 N}{\partial h_I^2}}{\frac{\partial^2 N}{\partial h_I \partial a} \frac{\partial^2 N}{\partial a^2}} - \frac{\frac{\partial^2 N}{\partial h_I \partial f} \frac{\partial^2 N}{\partial h_I \partial a}}{\frac{\partial^2 N}{\partial h_I \partial a} \frac{\partial^2 N}{\partial h_I \partial a}} \right)}{\frac{\frac{\partial^2 N}{\partial h_I^2} \frac{\partial^2 N}{\partial a^2}}{\frac{\partial^2 N}{\partial h_I \partial a} \frac{\partial^2 N}{\partial h_I \partial a}} - \frac{\frac{\partial^2 N}{\partial h_I \partial a} \frac{\partial^2 N}{\partial h_I \partial a}}{\frac{\partial^2 N}{\partial h_I \partial a} \frac{\partial^2 N}{\partial h_I \partial a}}}.$$

It is reasonable to assume that the direct effect dominates the indirect effect. Therefore,  $\frac{\partial^2 N}{\partial a \partial f} \frac{\partial^2 N}{\partial h_I^2} > \frac{\partial^2 N}{\partial h_I \partial f} \frac{\partial^2 N}{\partial h_I \partial a}$  and  $\frac{\partial^2 N}{\partial h_I^2} \frac{\partial^2 N}{\partial a^2} > \frac{\partial^2 N}{\partial h_I \partial a} \frac{\partial^2 N}{\partial h_I \partial a}$ . This implies that  $\frac{da}{df} > 0$ . This assumption may also be justified by using the actual derivatives of the profit function:

$$(A9) \quad \frac{\partial^2 N}{\partial a \partial f} = -\frac{\partial \pi(m, a)}{\partial a} h_I,$$

$$(A10) \quad \frac{\partial^2 N}{\partial h_I^2} = -\frac{\partial^2 c(\bar{h}, h_I, x)}{\partial h_I^2} - \frac{\partial^2 d(h_I, a)}{\partial h_I^2},$$

$$(A11) \quad \frac{\partial^2 N}{\partial h_I \partial f} = -\pi(m, a),$$

$$(A12) \quad \frac{\partial^2 N}{\partial h_I \partial a} = -\frac{\partial \pi(m, a)}{\partial a} f - \frac{\partial^2 d(h_I, a)}{\partial h_I \partial a},$$

$$(A13) \quad \frac{\partial^2 N}{\partial a^2} = -\frac{\partial^2 \pi}{\partial a^2} f h_I - \frac{\partial^2 d(h_I, a)}{\partial h_I \partial a}.$$

Writing (A8) with (A9)–(A13) yields:

$$\frac{da}{df} = \frac{\frac{\partial \pi(m, a)}{\partial a} h_I \left( \frac{\partial^2 c(\bar{h}, h_I, x)}{\partial h_I^2} + \frac{\partial^2 d(h_I, a)}{\partial h_I^2} \right) - \pi(m, a) \frac{\partial \pi(m, a)}{\partial a} \left( f + \frac{\partial^2 d(h_I, a)}{\partial h_I \partial a} \right)}{\left( \frac{\partial^2 c(\bar{h}, h_I, x)}{\partial h_I^2} + \frac{\partial^2 d(h_I, a)}{\partial h_I^2} \right) \left( \frac{\partial^2 \pi}{\partial a^2} f h_I - \frac{\partial^2 d(h_I, a)}{\partial h_I \partial a} \right) - \pi(m, a) \frac{\partial \pi(m, a)}{\partial a} \left( f + \frac{\partial^2 d(h_I, a)}{\partial h_I \partial a} \right)}.$$

(A14)

If  $\frac{da}{df} > 0$ , the right-hand side of (A14) should also be positive. This can be obtained by the numerator and the denominator being positive simultaneously, implying the two following equations must be fulfilled simultaneously:<sup>20</sup>

$$\frac{\partial \pi(m, a)}{\partial a} h_I \left( \frac{\partial^2 c(\bar{h}, h_I, x)}{\partial h_I^2} + \frac{\partial^2 d(h_I, a)}{\partial h_I^2} \right) > \pi(m, a) \frac{\partial \pi(m, a)}{\partial a} \left( f + \frac{\partial^2 d(h_I, a)}{\partial h_I \partial a} \right),$$

(A15)

$$\left( \frac{\partial^2 c(\bar{h}, h_I, x)}{\partial h_I^2} + \frac{\partial^2 d(h_I, a)}{\partial h_I^2} \right) \left( \frac{\partial^2 \pi}{\partial a^2} f h_I - \frac{\partial^2 d(h_I, a)}{\partial h_I \partial a} \right) > \pi(m, a) \frac{\partial \pi(m, a)}{\partial a} \left( f + \frac{\partial^2 d(h_I, a)}{\partial h_I \partial a} \right).$$

(A16)

Because  $h_I$  is large, it is likely that (A15) and (A16) is fulfilled. The limits on the harvest are then:

$$h_I > \frac{\pi(m, a) \frac{\partial \pi(m, a)}{\partial a} \left( f + \frac{\partial^2 d(h_I, a)}{\partial h_I \partial a} \right)}{\frac{\partial \pi(m, a)}{\partial a} \left( \frac{\partial^2 c(\bar{h}, h_I, x)}{\partial h_I^2} + \frac{\partial^2 d(h_I, a)}{\partial h_I^2} \right)},$$

(A17)

$$h_I > \frac{\left( \frac{\partial^2 c(\bar{h}, h_I, x)}{\partial h_I^2} + \frac{\partial^2 d(h_I, a)}{\partial h_I^2} \right) + \pi(m, a) \frac{\partial \pi(m, a)}{\partial a} \left( f + \frac{\partial^2 d(h_I, a)}{\partial h_I \partial a} \right)}{\left( \frac{\partial^2 c(\bar{h}, h_I, x)}{\partial h_I^2} + \frac{\partial^2 d(h_I, a)}{\partial h_I^2} \right) \left( \frac{\partial^2 \pi}{\partial a^2} \right) f}.$$

(A18)

We assume that (A16) and (A17) is fulfilled and then that  $\frac{\partial a}{\partial f} > 0$ .

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