Individual vs. Collective Quotas in Fisheries Management: Efficiency and Distributional Impacts

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Abstract: This paper considers four alternative policies for controlling harvest within a fishery: (1) individual limits without a permit market, (2) individual limits with a permit market, (3) a collective limit with individual decisions, and (4) a collective limit with collective decisions. We focus on three issues: risk pooling, moral hazard, and the role of permit trading. We find that, as long as the penalty rates are set appropriately, all four policies can yield the first best. Thus, with a welfare-maximizing regulator who sets policy parameters optimally, there is no efficiency basis for preferring one over the other. In particular, allowing permit trading and risk pooling does not increase efficiency. However, the four policies differ in terms of their impact on the expected profit of harvesters. Thus, there is a distributional basis for distinguishing among the four policies. We find that in the absence of permit trading and moral hazard, the collective limit with collective decisions yields higher expected profits than the individual limits. However, the moral hazard problem that arises under the collective limit with individual decisions makes harvesters worse off in terms of distributional impact. Finally, although the permit market provides an opportunity for risk spreading for harvesters, the potential moral hazard problem leads to a detrimental distributional impact on harvesters under permit trading. Thus, contrary to standard results, here allowing permits to be traded has no efficiency impact and makes harvesters worse off.

Key words: collective limits, risk pooling, moral hazard, permit trading, distributional impact

1. Introduction

Innovations in fisheries management in the last few decades have focused on designing different mechanisms to allocate property rights. For example, catch shares in the form of individual fishing quotas (IFQs) or individual tradable quotas (ITQs) have received considerable attention. As an alternative to approaches based on granting rights to individuals or vessels, collective approaches grant property rights collectively to a group of individuals or vessels. Collective management approaches can involve a variety of institutional forms, including fishing cooperatives and territorial use rights fisheries (TURFs). They have the potential to improve management in situations where the returns or rewards that one member of the group receives depend not only on his own decisions/actions but also on those of other members of the group, or, in other words, when one party's actions can impose benefits or costs on others within the group.

The interdependence among harvesters in a fishery can arise from two sources. First, it can stem from the biological or economic environment in which members of the group operate. For example, when harvesters compete for prime fishing locations, times, or stocks or when the price a harvester receives for his landings depends on the landings of others as well, then one harvester's revenue will be affected by the harvest decisions of others. In this case, harvesters within a given fishery impose intra-fishery externalities on other harvesters (Cancino et al., 2007; Deacon, 2012; Holland, 2004; Segerson, 2014). Alternatively, even in the absence of ecological or market interactions, interdependence can arise from externally-imposed constraints, such as collective limits on harvest of a target species or bycatch imposed by regulators or fishery managers (Abbott and Wilen, 2009; Segerson, 2011). These quotas typically seek to limit fishing activity either to reduce intra-fishery externalities or to reduce externalities borne outside the fishery, resulting, for example, from bycatch of non-commercial (sometimes endangered) species, ecological impacts of habitat degradation from disruptive fishing, or other non-

commercial uses of the marine environment (e.g., recreational fishing) (Arnason, 2012; Holland, 2004; Holland and Schnier, 2006; Wilen et al. 2012). Under a collective quota, use of part of the collective quota by one harvester implies that less is available for use by others, which implies that the opportunities available to one harvester are impacted by the decisions of others. Regardless of whether the interdependencies arise from intra-fishery externalities and/or solely from externally-imposed aggregate constraints, a collective assignment of rights or limits provides an incentive for members of the group to seek to collectively address these interdependencies (Segerson, 2014).

Collective approaches have also been advocated as a mechanism for risk pooling in fisheries, especially when faced with uncertainty (Holland, 2010; Holland and Herrera, 2012; Segerson, 2011). The potential benefits of pooling are usually described in terms of reducing risk of income fluctuation and net damages, by pooling input and maintenance costs (Platteau and Seki, 2001), or sharing revenue or profit (Gaspart and Seki, 2003; Heintzelman et al. 2009; Kaffine and Costello, 2011; Platteau and Seki, 2001; Uchida and Baba, 2008; Uchida and Watenobe, 2008). Information sharing among members in the pool further dampens the impact of uncertainty (Gaspart and Seki, 2003; Platteau and Seki, 2001).

However, collective approaches can also create moral hazard, especially when the ownership of resources or quota is not clearly defined at the individual harvester or vessel level. For example, under collective quotas, harvesters have incentives to 'race-to-fish' if the fishing season will be closed once the aggregate limits are reached and they cannot be accountable for the past overfishing (Copes, 1986; Pascoe, 2010). The common pool structure causes harvesters to ignore the negative externality of their behavior on the overall season length, which leads to wasted target species catch, a shortened harvest season and reduced rent (Abbott and Wilen, 2009). The moral hazard problem is even more serious for large pools with heterogeneous fishermen and asymmetric information (Holland, 2010). Furthermore, collective approaches often involve a pooling of revenues, which might also induce an incentive to shirk

and free ride on the efforts of others (Cancino et al. 2007; Heintzelman et al. 2009; Platteau and Seki, 2001; Uchida and Watanobe, 2008). Thus, a fundamental question regarding collective approaches is the potential tradeoff between the effects of risk pooling and moral hazard.

Although collective approaches provide a means of spreading risk, they are not the only mechanism that can be used for this purpose. For example, the transferability of individual quotas provides a mechanism for risk spreading for individuals. The potential for trading quotas effectively allows harvesters to pool their permits and redistribute the quota through trading in the market. Compared to non-transferable quota mechanism, efficient quota markets reduce the risk of individual harvester's income fluctuation (Holland, 2010). Although the advantages and disadvantages of the use of ITQs have been widely recognized,[1] there is surprisingly little discussion of their role as a mechanism for spreading risk in fisheries. The advantage of tradable quotas in risk sharing has more broadly been recognized in the literature on emission permits. For example, Mrozek and Keeler (2004) note that tradable permit markets provide firms an opportunity to respond to uncertainty, because the permit market smooths the outcomes across firms, making the violation dependent on the joint randomness instead of the randomness for individuals. In addition, allowing banking and/or borrowing between periods further reduces the impact of intertemporal uncertainty (e.g., Innes, 2003).

There are at least two gaps in the literature on the use of collective quotas in fisheries management. First, theoretical studies in the literature typically focus on either collective approaches (e.g., Abbott and Wilen, 2009; Gaspart and Seki, 2003; Heintzelman et al. 2009; Uchida and Wilen, 2005) or individual quotas (e.g., Boyce, 1996). Among those papers comparing these two alternatives,

[1] For example, although ITQs have been shown to be effective in increasing efficiency in fisheries, they can lead to an inefficient spatial or intraseasonal distribution of harvest activities (Anderson, 1989; Boyce, 1992; Clark, 1980; Costello and Deacon, 2007; Holland, 2004; Wilen et al., 2012).

most are descriptive without a unified theoretical framework (Cancino et al., 2007; Holland, 2004; Wilen et al. 2012). Secondly, in the context of fisheries management, policy parameters, e.g., tax rates or penalty rates, are typically set exogenously, rather than optimally chosen (Abbott and Wilen, 2009; Bisack and Sutinen, 2006; Holland and Herrera, 2012; Herrera, 2005; Mrozek and Keeler, 2004).

This paper presents a unified model that can be used to illustrate some incentive issues that arise in the use of individual quotas and collective quotas, in a context where regulators can set policy parameters optimally to affect harvesting incentives. We focus on three issues that are potentially important in this context, namely, risk pooling, moral hazard, and the role of permit trading. We analyze four alternative policies: (1) individual limits without permit trading (IFQs), (2) individual limits with permit trading (ITQs), (3) a collective limit with individual decisions, and (4) a collective limit with collective decisions.[2] All four of these approaches have been used in fisheries management.[3] We focus

[2] Since harvesters in general have no incentive to trade permits under collective limits, we do not consider permit markets for the cases that involve collective limits.

[3] For example, IFQs have been used in the Namibian orange roughy fishery (Costello, 2012) and within *Benthic Regime of Extraction* (BRE) zones in Chile (Cancino et al. 2007). Since first introduced in the Netherlands flatfish fishery and the Icelandic herring fishery in the 1970s, ITQs have been adopted in more than 22 countries (Arnason, 2012). Examples include the Mid-Atlantic clam and quahog fisheries, the South Atlantic wreckfish fisheries and the North Pacific halibut and sablefish fisheries in the U.S (Criddle and Macinko, 2000), the scallops fishery in New Zealand (Mincher, 2008), and the halibut fishery in British Columbia (Grafton et al., 2000). Collectively approaches have been used in a variety of contexts. The extent to which the assignment of collective rights or responsibilities leads to collective (i.e., coordinated) decisions can vary significantly, ranging anywhere from full coordination (where, for example, a manager or committee makes all decisions for all members of the group) to no coordination (where each member of the group continues to act independently despite the collective constraint) (Segerson, 2014; Uchida and Wilen, 2005). For example, the industry-wide sea turtle bycatch limit in the Pacific longline swordfish fishery imposes an aggregate limit on bycatch across all vessels, but vessel owners do not collectively manage the fishery or bycatch (Segerson, 2010). Likewise, in many of the New England groundfish sectors, the sector-wide catch allocation is distributed by the sector to individual sector members, who then make independent decisions about how to use their share of the total quota (Holland and Weirsma, 2010). A similar approach is used in the Bering Sea Pollock Conservation Cooperative (Wilen and Richardson, 2008) and Chile's *loco* fishing cooperatives (Uchida and Wilen,

on policy-induced interdependence, in which the regulator sets quotas (either individual or collective) and then seeks to maximize social welfare by optimally setting the "penalty" for exceeding the quota. Rather than closing the fishery when the quota is reached, we assume that individuals or the group can effectively purchase additional quota at a fixed price, or, equivalently (in terms of the model), pay a penalty that is proportional to the amount by which the quota is exceeded.[4] The mechanism of the proportional penalty is similar to the system of deemed values implemented in New Zealand (Holland, 2010; Sanchirico, et al., 2006; Soboil and Craig, 2008), or a "safety valve" under an emissions trading system (Burtraw et al., 2010; Fell et al., 2010, 2012).

We find that, when optimally designed, all four alternative policies can yield the first best (even with risk pooling and moral hazard and with and without permit trading). Thus, there is no efficiency basis for preferring one over the others. However, because the four alternatives create different harvesting incentives, the optimal penalties differ, which in turn leads to differences in individual and industry-wide expected net profits across the policies. This implies that, although the efficiency impacts are the same, the four policies have different distributional impacts.

2005). In contrast, the Alaskan Chignik salmon cooperative was granted a collective allowable catch and managed that allocation cooperatively (Deacon, et al., 2008). Similarly, a local fishing organization manages the sakuraebi fishery and shiroebi fishery in Japan through centralized coordination (Platteau and Seki, 2001; Uchida and Baba, 2008; Uchida and Wilen, 2005), as does the deep-sea crab fishery in New Zealand (Soboil and Craig, 2008) and the walleye pollack (suketoudara) fishery in Japan (Uchida and Watanobe, 2008).

[4] Proportional penalties have been shown to be more efficient than season closures as a means of creating incentives. See, for example, (e.g., Segerson, 2011).

Since regulators are typically concerned about the distributional as well as the efficiency impacts of policies,[5] a key question is how these alternatives rank in terms of distributional impacts on harvesters, given the optimally designed policies. We find that the moral hazard problem that arises under the collective limit with individual decisions makes harvesters worse off in terms of distributional impact. In the absence of permit trading and moral hazard, as a result of risk pooling, the collective limit (with collective decisions) yields higher expected profits than the individual limits. Finally, although the permit market provides an opportunity for risk spreading for harvesters, the potential moral hazard problem leads to a detrimental distributional impact on harvesters under permit trading. This is in contrast to the standard result that allowing permits to be traded makes harvesters better off.

The paper is organized as follows. In section 2, we present the basic model and the social planner's problem to derive the first-best outcome. Section 3 presents the models for harvesters under individual quotas and collective quotas. Section 4 then compares the four scenarios given optimally designed policies, in terms of probabilities of violation, expected magnitude of violation and expected penalties (and hence expected net profits). In section 5, we discuss the incentives created by the alternative policies. Section 6 concludes.

Finally, we note that, although the analysis here is presented in terms of fisheries management, the basic question of the use of individual vs. collective limits is relevant in many other contexts as well, including control of agricultural pollution, the design of liability limits, and the use of industry-wide

[5] Reforms in fisheries management sometimes pursue a better distributional outcome at the expense of reduced efficiency, such as in the battles over limited entry in North America and the ban on efficient fish traps in Alaska and Washington (Grainger and Parker, 2013). Amendment of the Magnuson-Stevens Fishery Conservation and Management Act in 1996 focused mainly on distributional issues (Matulich et al. 2001). In addition, more recent critiques of ITQs focus on fairness, such as the distribution of rents (Cancino et al. 2007).

voluntary agreements. Thus, the results derived here could potentially have applicability in these other contexts as well.

2. The Basic Model and First-Best Outcome

We consider a stylized model comprised of two identical harvesters, each of whom owns a single vessel that engages in fishing effort that leads to a stochastic amount of harvest. By assuming a single effort level for each harvester, we focus on the key question of how much to fish and abstract from a number of important real-world considerations in fisheries management, including the spatial and temporal dimensions of fishing effort (i.e., where and when to fish), multi-species interactions, and the impact of fishing decisions on product quality and/or price.[6] Although the model is a simplification of actual fishing behavior, it nonetheless is able to capture the fundamental features that we seek to focus on in this paper, namely, moral hazard, risk pooling, and the role of permit trading.

More specifically, let e_i be the effort undertaken by harvester i ($i = 1, 2$). The harvest amount h_i is a function of the effort level and a random variable ε_i: $h_i = \varepsilon_i F(e_i)$, where $F(e_i) = \phi e_i$ ($i = 1, 2$).[7] The stochastic elements of the two harvesters are assumed to be uncorrelated. For simplicity, we assume ϕ=1

[6] The spatial and temporal arrangement of fishing effort has been studied in, for example, Cancino et al. (2007), Deacon et al. (2008), Deacon (2012), and Uchida and Baba (2008). Multi-species interactions have been explored in, e.g., Cancino et al. (2007), Holland (2004), Newell et al (2005) and Wilen et al. (2012). The impact of fishing decisions on product quality and/or price and other market-side incentives are studied in Cancino et al. (2007), Deacon (2012), Matulich et al. (2001), Platteau and Seki (2001), and Wilen and Richardson (2008).

[7] Although the model is cast in terms of harvest and quotas for a target species, it could also be interpreted in the context of quotas on bycatch, based on the assumption that there exists some proportionality between harvest of the target species and harvest of bycatch.

and ε_i is uniformly distributed over $[0,1]$. Then h_i is uniformly distributed over $[0, e_i]$. Thus, e_i can also be interpreted as the maximum possible harvest. The expected pre-penalty profit for harvester i is $E[\pi(e_i, \varepsilon_i)] = pE(h_i) - C(e_i) = pE[\varepsilon_i F(e_i)] - C(e_i)$, where $C'(\cdot)>0$, $C''(\cdot)>0$. Here we assume $C(e_i) = e_i^2$ and the price is normalized to one.[8] Given these assumptions, $E[\pi(e_i, \varepsilon_i)] = 0.5e_i - e_i^2$.

Suppose that harvest activity generates social damages, which are denoted by $D(X)$, where $X = h_1 + h_2$ is total harvest amount and $D(\cdot)$ is the damage function. This can be interpreted as the damage from the associated bycatch or the discards of non-targeted species, impacts on other fisheries through multi-species interactions (e.g., predator-prey relationships), or ecological damages from fishing methods that harm marine habitats.[9] Thus, we focus on the case of damages that are external to the group of harvesters, rather than externalities imposed within the group (the classic commons problem).[10] For simplicity, we assume a linear damage function, i.e., $D(X) = dX$, where $d < 1$.[11]

The efficient effort level will maximize social welfare:

[8] Under this assumption, harvesters cannot affect price through their fishing decisions.

[9] As mentioned in the introduction, this type of external damages has also been pointed out in Arnason (2012), Holland (2004), Holland and Schnier (2006) and Wilen et al. (2012).

[10] This implies that in our context efficient outcomes cannot be assured simply by merging the two harvesters under a single "sole owner", which is often suggested as a solution to the commons problem (e.g., Holland, 2004; Scott, 1955; Smith, 1968; Wilen et al. 2012).

[11] If d is greater than or equal to one, then the marginal net social benefit of effort is zero or negative, implying that it would be optimal to shut down the fishery.

$$\max_{e_1,e_2} \sum_{i=1}^{2} E[\pi(e_i,\varepsilon_i)] - E[D(X)] = \sum_{i=1}^{2}(0.5e_i - e_i^2) - 0.5d(e_1+e_2). \tag{1}$$

This problem yields an interior solution given by:

$$e_i^* = \frac{1-d}{4} \quad ,$$

for $i = 1, 2$. The efficient effort level is the level where the expected marginal social benefit of an increase in effort (in the form of increased expected profits) equals the expected marginal social cost (in the form of increased expected social damage).

Without any policy intervention, harvesters simply seek to maximize expected profits. The competitive equilibrium will be $e_i = 0.25$, for $i = 1, 2$, which exceed the socially efficient levels of effort. This reflects the classic "over-fishing" that results from the externality imposed by fishing. While here we model this externality as arising from social damages imposed by fishing activities on others, it is analogous to the over-grazing or over-fishing that results from the commons problem, where the activities of one member of the group impose an externality on others in the group.

3. Market Equilibria and Optimal Policy Designs

We consider four alternative policies that have been adopted in fisheries management: (1) individual limits on allowable harvest without permit trading, (2) individual limits with permit trading, (3) collective limits when the TAC is then allocated to individuals within the group who make individual decisions, and (4) collective limits when the group makes collective decisions. We assume that harvesters or groups have to pay a proportional penalty for exceeding their quota. As noted above, this is analogous to New Zealand's deemed value system or the use of a safety valve in emission trading. In each case, we first characterize private decisions under these alternative policies, conditional on the

harvest limits and penalties for violating those limits. This is similar to what is done in the literature when penalties are treated as exogenously set (e.g., Abbott and Wilen, 2009; Bisack and Sutinen, 2006; Holland and Herrera, 2012; Herrera, 2005; Mrozek and Keeler, 2004). Given these responses, we then let the regulator choose the penalty levels under the different scenarios to maximize social welfare. For each policy, this allows us to answer the question of whether the policy can be designed to induce first-best effort levels, and, if so, how.

3.1. Individual limits without trading (IFQs)

Assume the regulator allocates quota $\bar{h}$ to each harvester and the quota is not tradable. The harvester incurs no fine if the harvest is no more than the quota. However, if the quota limit is violated, the harvester has to pay a proportional penalty with fine rate equal to k. The expected penalty is then given by:

$$\Phi_i^I = \begin{cases} 0, & if \quad h_i \le \bar{h}, \\ k(h_i - \bar{h}), & if \quad h_i > \bar{h}, \end{cases} \tag{2}$$

where the superscript I denotes the case of individual limits without trading.

Note that, because harvest is stochastic, harvesters cannot control with certainty whether they exceed their quotas. However, they can choose their effort levels to reduce the probability that the quota will be violated and hence reduce the expected penalty. Specifically, the optimization problem for harvester i $(i = 1, 2)$ is:

$$\max_{e_i} E[\pi(e_i,\varepsilon_i)] - E[\Phi_i^I] = E[\varepsilon_i F(e_i)] - C(e_i) - E[k(h_i - \bar{h}) \mid h_i > \bar{h}]\Pr(h_i > \bar{h})$$

$$= \begin{cases} 0.5e_i - e_i^2 - k\dfrac{(e_i - \bar{h})^2}{2e_i}, & if \quad e_i > \bar{h}, \\ 0.5e_i - e_i^2, & if \quad e_i \le \bar{h}. \end{cases} \tag{3}$$

The optimal interior solution e_i^I $(i=1,2)$ in the range $e_i > \bar{h}$ satisfies the first order condition:

$$\frac{dE[\pi(e_i,\varepsilon_i)]}{de_i} - \frac{dE[\Phi_i^I]}{de_i} = 0.5 - 2e_i - 0.5k(1 - \bar{h}^2 / e_i^2) = 0. \tag{4}$$

Thus, effort is chosen at the point where the marginal benefit from increased expected pre-penalty profits equals the marginal cost from the increased expected penalty. [12]

Now assume that the regulator sets the policy parameters $(\bar{h}, k)$ optimally to induce efficient effort. Since there is one degree of freedom, the regulator can set the optimal k^*, given $\bar{h}$. If $\bar{h} \ge e^*$, the harvests will never violate the limit and imposing a penalty has no effect, i.e., it will not be effective in reducing effort. Thus, a welfare-maximizing regulator will want to set $\bar{h} < e^* = \frac{1-d}{4}$. Thus, in deriving the optimal penalty, we assume that $\bar{h} < e^*$. Comparing the first order conditions in this scenario with those for the social planner's problem, we have the following result (see the appendix for proofs of all results and propositions):

Proposition 1. *Under individual limits without trading, by setting* $\bar{h}$ *at any level smaller than* e^* *and* $k_I^* = (\frac{e^{*2}}{e^{*2} - \bar{h}^2})d$ *, the regulator can induce the efficient effort levels by both harvesters.*

[12] Note that this first order condition only holds for the interior solution. It is not an exclusive description of the optimal solutions. When the optimal solutions are at the dividing point $\bar{h}$, the above first order condition does not necessarily hold. This is also true for the first order conditions below.

Proposition 1 shows that, even when harvest is stochastic, the regulator can induce the first best effort levels by adjusting the penalty rate k (for a given quota $\bar{h}$) to internalize the expected social cost of the harvesters' behavior. We discuss the optimal penalty rate in more detail below, after first deriving the equilibrium under the other three policy scenarios.

3.2. Individual limits with trading (ITQs)

Now suppose the harvesters are allowed to trade their quotas. There will be no role for *ex ante* trading, because we assume the two harvesters are identical, which implies that they form the same expectations and have no incentive to conduct any *ex ante* trade. However, they might have an incentive to trade *ex post* when they observe the realized harvest. Therefore, we will study the case with *ex post* trading. As mentioned above, allowing harvesters to trade quota provides an opportunity for risk spreading across the two harvesters.

Following Mrozek and Keeler (2004), we consider the model with two-period decision making. In the first period, the regulator allocates the quota $\bar{h}$ to each harvester. Harvesters make decisions about their effort levels, based on the expectation of the harvest amounts and knowledge of the ability to trade quota *ex post.* In the second period, the harvesters observe their realized harvests, and choose how much quota to buy or to sell. We assume the regulator can observe the realized harvests and trading amounts. The regulator imposes an *ex post* penalty with the proportional penalty rate equal to k if harvester i's harvest exceeds the amount of quota held by harvester i. That is,

$$\Phi_i^P = \begin{cases} 0, & if \quad h_i \le \bar{h} + t_i, \\ k(h_i - \bar{h} - t_i), & if \quad h_i > \bar{h} + t_i, \end{cases} \tag{5}$$

where t_i is the quantity of quota purchased (if it is positive) or sold (if it is negative) and $(\bar{h}+t_i)$ is the total quantity held by harvester i. The superscript P denotes the case of individual limits with trading.

To determine the equilibrium when trading is allowed, we solve the model backwards. In the second period, harvester i (i=1,2) wants to minimize total costs in the second period (TC_i), given the quota market and the penalty structure. He makes choices based on the realized harvests, so there is no uncertainty in the second period. The harvester i's problem is then:

$$\begin{aligned}&\min_{t_i} TC_i^P = \Phi_i^P + t_i r \\ &= \begin{cases} rt_i, \quad if \quad h_i \le \bar{h} + t_i, \\ k(h_i - \bar{h} - t_i) + rt_i = (r-k)t_i + k(h_i - \bar{h}), \quad if \quad h_i > \bar{h} + t_i, \end{cases}\end{aligned} \tag{6}$$

where r is the per unit quota price, which is endogenously determined by supply and demand for quota.[13] If the total realized harvest is less than the aggregate (i.e., combined) quantity allocated (i.e., demand is less than supply), quota will have no market value, i.e., $r=0$. We assume the harvesters are willing to give the redundant quota to others for free in this case. In contrast, if the total realized harvest is greater than the total quota available (i.e., demand is greater than supply), the quota price will be driven up to the penalty rate k. That is,

$$\begin{cases} r = 0, \quad if \quad h_1 + h_2 < 2\bar{h}, \\ r = k, \quad if \quad h_1 + h_2 > 2\bar{h}, \\ 0 \le r \le k, \quad if \quad h_1 + h_2 = 2\bar{h}. \end{cases} \tag{7}$$

[13] Although our model includes only two harvesters, we assume that the quota market is competitive, i.e., that neither harvester has market power in the quota market.

The decision to buy or sell quota is based on a comparison of marginal benefit and marginal cost. The marginal benefit of buying an additional unit of quota is the reduced penalty k, while the marginal cost is the quota price r. Thus, the optimal purchase/sale decision and the corresponding total costs in the second period are given by:

(i) If $h_1 + h_2 = 2\bar{h}$, which implies $0 \le r \le k$, then

$t_i^* = h_i - \bar{h}$, and $TC_i = r(h_i - \bar{h})$.

(ii) If $h_1 + h_2 > 2\bar{h}$, which implies $r = k$, then

any t_i in the range $[-\bar{h}, h_i - \bar{h}]$ is optimal and yields the same total cost,

$TC_i = r(h_i - \bar{h}) = k(h_i - \bar{h})$.

(iii) If $h_1 + h_2 < 2\bar{h}$, which implies $r = 0$, then quota is reallocated freely and no penalties are incurred, which implies $TC_i = 0$.

Anticipating the expected outcome in the second period (and ignoring any discounting), in the first period, each harvester chooses an effort level to maximize his expected net profit (after deducting the expected spending/receipt from the quota market and the penalty):

$$\max_{e_i} E[\pi(e_i, \varepsilon_i)] - E[TC_i^P] = 0.5e_i - e_i^2 - E[TC_i], \tag{8}$$

where $E[TC_i^P]$ is the first period expectation of the total costs from trading and penalties in the second period, given by[14]

$$\begin{aligned} E[TC_i^P] &= P(h_1 + h_2 > 2\bar{h}) * E[TC_i \mid h_1 + h_2 > 2\bar{h}] \\ &= P(h_1 + h_2 > 2\bar{h}) * E[k(h_i - \bar{h}) \mid h_1 + h_2 > 2\bar{h}]. \end{aligned} \tag{9}$$

Substituting $E[TC_i^P]$ into the objective function, we have

$$\max_{e_i} E[\pi(e_i, \varepsilon_i)] - E[TC_i^P] = 0.5e_i - e_i^2 - P(h_1 + h_2 > 2\bar{h}) * E[k(h_i - \bar{h}) \mid h_1 + h_2 > 2\bar{h}]. \tag{10}$$

We assume the two harvesters have perfect information and have full knowledge of the cost functions of the other firm. A Nash equilibrium e_i^P $(i = 1, 2)$ satisfies the following first order conditions:

$$\frac{\partial E[\pi(e_i, \varepsilon_i)]}{\partial e_i} - \frac{\partial E[TC_i^P]}{\partial e_i} = 0.5 - 2e_i - \frac{\partial [P(h_1 + h_2 > 2\bar{h}) * E\{k(h_i - \bar{h}) \mid h_1 + h_2 > 2\bar{h}\}]}{\partial e_i} = 0, \tag{11}$$

for $i = 1, 2$. Thus, the optimal effort is at the point where the marginal benefit from increased expected pre-penalty profits equals the marginal cost from increased expected total spending on quota trading and penalties. Given identical harvesters, we will focus on symmetric, pure strategic Nash equilibria, similar to Abbott and Wilen (2009). Specifically, we will only focus on the cases $e_1 = e_2 > 2\bar{h}$ and $e_1 = e_2 \le 2\bar{h} < e_1 + e_2$ when we solve the model.

Comparing the first order conditions under individual limits with trading with those for the social planner's problem, we have the following conclusion:

[14] More precisely, $E[TC_i] = P(h_1 + h_2 > 2\bar{h}) * E[TC_i \mid h_1 + h_2 > 2\bar{h}] + P(h_1 + h_2 = 2\bar{h}) * E[TC_i \mid h_1 + h_2 = 2\bar{h}]$ $+ P(h_1 + h_2 < 2\bar{h}) * E[TC_i \mid h_1 + h_2 < 2\bar{h}]$. We have $P(h_1 + h_2 = 2\bar{h}) = 0$, because the probability function is continuous. Moreover, $E[TC_i \mid h_1 + h_2 < 2\bar{h}] = 0$. Therefore, the total expected costs can be simplified as $E[TC_i] = P(h_1 + h_2 > 2\bar{h}) * E[TC_i \mid h_1 + h_2 > 2\bar{h}]$.

Proposition 2. *Under individual limits with trading, by setting* $\bar{h}$ *at any level smaller than* e^**, and*

$$k_P^* = \begin{cases} \dfrac{3e^{*3}d}{(3e^{*3} + 4\bar{h}^3 - 6\bar{h}^2 e^*)}, & if \quad 0 < \bar{h} < 0.5e^*, \\ \dfrac{3e^{*3}d}{2(e^* - \bar{h})(2e^{*2} + 2\bar{h}^2 - \bar{h}e^*)}, & if \quad 0.5e^* \le \bar{h} < e^*, \end{cases}$$

the regulator can induce the efficient effort levels by both harvesters.

Thus, with identical harvesters, by appropriately setting the penalty rates, the regulator can induce first best effort levels regardless of whether trading is allowed or not.

3.3. Collective limit with individual decisions

Instead of distributing the quota to individual harvesters, it is also possible to allocate the collective quota, i.e., the total allowable catch (TAC), to a group as a whole. In this case, the members in the group will face a penalty if and only if the collective limit is exceeded. With collective limits, the group must decide whether it will make collective decisions about effort levels or allow each member of the group to make his own effort decision.[15] We assume first that each member within the group makes its own decision independently. However, if the collective quota is violated, the total penalty for the group will be $k(h_1 + h_2 - 2\bar{h})$, which is comparable to the case under individual limits. We assume that this total penalty is shared equally by the harvesters. Thus, the penalty for harvester i $(i = 1, 2)$ is given by:

[15] Note that when faced with a group penalty, harvesters in both these two cases have no incentive to trade quota either *ex ante* or *ex post*, because they are not being fined for violating individual limits, implying that the marginal benefit of purchasing additional unit of quota is zero. Even with heterogeneous firms, they have no incentive to trade quotas either *ex ante* or *ex post* under a collective policy, because the marginal benefit of buying quota is still zero. For this reason, we do not consider quota trading for the policies with collective limits.

$$\Phi_i^N = \begin{cases} 0, & if \quad h_1 + h_2 \le 2\bar{h}, \\ 0.5k(h_1 + h_2 - 2\bar{h}), & if \quad h_1 + h_2 > 2\bar{h}, \end{cases} \tag{12}$$

where the superscript N denotes the case of a collective limit with individual decisions.

We assume each harvester maximizes his own expected net profit, taking the choices of others as given:

$$\begin{aligned} &\max_{e_i} E[\pi(e_i, \varepsilon_i)] - E[\Phi_i^N] \\ &= 0.5e_i - e_i^2 - E[0.5k(h_1 + h_2 - 2\bar{h}) \mid h_1 + h_2 > 2\bar{h}]\Pr(h_1 + h_2 > 2\bar{h}). \end{aligned} \tag{13}$$

The necessary conditions for a Nash equilibrium are:

$$\frac{\partial E[\pi(e_i, \varepsilon_i)]}{\partial e_i} - \frac{\partial E[\Phi_i^N]}{\partial e_i} = 0.5 - 2e_i - 0.5k\frac{\partial\{E[(h_1 + h_2 - 2\bar{h}) \mid h_1 + h_2 > 2\bar{h}]\Pr(h_1 + h_2 > 2\bar{h})\}}{\partial e_i} = 0, \tag{14}$$

for $i = 1, 2$. For each harvester, the optimal effort is at the point where the marginal benefit from increased expected pre-penalty profits equals the marginal cost from increased expected penalties, given the effort level of the other harvester. As in the case of individual limit with trading, we will focus on symmetric, pure strategic Nash equilibria.

Comparing the first order conditions in (14) with those for the social planner's problem, we have the following conclusion:

Proposition 3. *Under a collective limit with individual decisions, by setting* $\bar{h}$ *at any level smaller than* e^*, *and* $k_N^* = \begin{cases} \dfrac{6e^{*3}d}{(3e^{*3} - 8\bar{h}^3)}, & if \quad 0 < \bar{h} < 0.5e^*, \\ \dfrac{3e^{*3}d}{2(e^* - \bar{h})^2(e^* + 2\bar{h})}, & if \quad 0.5e^* \le \bar{h} < e^*, \end{cases}$

the regulator can induce the efficient effort levels by both harvesters.

Thus, even when harvesters are allowed to make individual decisions under a collective cap, given any $\bar{h} < e^*$, the regulator can still set the penalty rate to induce the first best effort levels.

3.4. Collective limit with collective decisions

Assume instead that the group makes decisions collectively. In this case, the objective of the group is to maximize joint profit. If the collective quota is exceeded, the whole group will be punished by a proportional penalty with marginal rate equal to k. That is, the aggregate penalty for the group is given by:

$$\Phi^S = \begin{cases} 0, & if \quad h_1 + h_2 \le 2\bar{h}, \\ k(h_1 + h_2 - 2\bar{h}), & if \quad h_1 + h_2 > 2\bar{h}, \end{cases} \tag{15}$$

where the superscript S denotes the case of a collective limit with collective decisions.

The problem for the whole group is:

$$\begin{aligned} &\max_{e_1, e_2} \sum_{i=1}^{2} E[\pi(e_i, \varepsilon_i)] - E[\Phi^s] \\ &= \{0.5e_1 - e_1^2 + 0.5e_2 - e_2^2\} - E[k(h_1 + h_2 - 2\bar{h}) \mid h_1 + h_2 > 2\bar{h}] \Pr(h_1 + h_2 > 2\bar{h}). \end{aligned} \tag{16}$$

The necessary conditions for interior solutions (e_1^S, e_2^S) are as follows:

$$\frac{\partial \sum_{i=1}^{2} E[\pi(e_i, \varepsilon_i)]}{\partial e_i} - \frac{\partial E[\Phi^S]}{\partial e_i} = 0.5 - 2e_i - k \frac{\partial \{E[(h_1 + h_2 - 2\bar{h}) \mid h_1 + h_2 > 2\bar{h}] \Pr(h_1 + h_2 > 2\bar{h})\}}{\partial e_i} = 0, \tag{17}$$

for $i = 1, 2$.

Comparing the first order conditions in this case with those for the social planner's problem, we have the following result:

Proposition 4. *Under a collective limit with collective decisions, by setting* $\bar{h}$ *at any level smaller than*

$$e^*, \text{ and } \quad k_S^* = \begin{cases} \dfrac{3e^{*3}d}{(3e^{*3} - 8\bar{h}^3)}, & \text{if} \quad 0 < \bar{h} < 0.5e^*, \\ \dfrac{3e^{*3}d}{4(e^* - \bar{h})^2(e^* + 2\bar{h})}, & \text{if} \quad 0.5e^* \le \bar{h} < e^*, \end{cases}$$

the regulator can induce the efficient effort levels by both harvesters.

Proposition 4 shows that, with the appropriate adjustment in the penalty rate, the regulator can induce efficiency effort levels for any $\bar{h} < e^*$ under the collective limit with collective decisions.

In summary, as long as the penalty rates are set appropriately given $\bar{h}$, all four policies can yield the first best. That is to say, with a welfare-maximizing regulator who sets policy parameters optimally, there is no efficiency basis for preferring one policy over the other. Nonetheless, when optimally designed, the policies still differ in two important respects: (1) the expected magnitudes of violation differ, which result from the differences in the probabilities of violation and conditional expected magnitudes of violation, and (2) the optimal penalty rates are different. As a result, the expected penalty that each harvester faces, and hence the impact on expected net profit, is different. This implies that the four alternatives have different distributional impacts on harvesters. This stems from the differing incentives that exist under the alternatives. In the following sections, we will compare the expected penalties under these alternatives, and the implications for their distributional impacts on harvesters.

4. Comparison of Expected Penalties

In equilibrium, by substituting the optimal penalty rates and efficient effort level for k and e, respectively, we get the expected penalties (or expected total spending on penalties and traded quota) for each harvester associated with the first-best outcomes under the above four scenarios:

$$E[\Phi_i^I] = k_I^* E[(h_i^* - \bar{h}) \mid h_i^* > \bar{h}] \Pr(h_i^* > \bar{h}), \tag{18}$$

$$E[TC_i^P] = k_p^* E[(h_i^* - \bar{h}) \mid h_1^* + h_2^* > 2\bar{h}] * P(h_1^* + h_2^* > 2\bar{h}), \tag{19}$$

$$E[\Phi_i^N] = 0.5 k_N^* E[(h_1^* + h_2^* - 2\bar{h}) \mid h_1^* + h_2^* > 2\bar{h}] \Pr(h_1^* + h_2^* > 2\bar{h}), \tag{20}$$

$$E[\Phi_i^S] = E[\Phi^S]/2 = 0.5 k_S^* E[(h_1^* + h_2^* - 2\bar{h}) \mid h_1^* + h_2^* > 2\bar{h}] \Pr(h_1^* + h_2^* > 2\bar{h}), \tag{21}$$

where $h_i^* = \varepsilon_i e^*$, for $i = 1, 2$. Comparing (18)-(21) shows that the expected penalties under the different policies will differ because of differences in the probabilities of violation, expected magnitude of the violations, and the penalty rates. We discuss each of these in turn.

4.1. Probabilities of violation

Recall that, since ε_i is uniformly distributed over $[0,1]$, $h_i^* = \varepsilon_i e^*$ is uniformly distributed over $[0, e^*]$. Thus, given e^*, the probability that the individual limit will be exceeded is:

$$\Pr(h_i^* > \bar{h}) = \begin{cases} 0, & if \quad \bar{h} \geq e^*, \\ 1 - \dfrac{\bar{h}}{e^*} & if \quad 0 \leq \bar{h} < e^*. \end{cases} \tag{22}$$

Define $x \equiv h_1^* + h_2^* = \varepsilon_1 e^* + \varepsilon_2 e^*$, which is the sum of two uniform distributions over $[0, e^*]$. The probability that the collective limit will be exceeded given efficient effort levels is given by:

$$\Pr(h_1^* + h_2^* > 2\bar{h}) = \Pr(\varepsilon_1 e^* + \varepsilon_2 e^* > 2\bar{h}) = \left\{ \begin{array}{l} 1 - \dfrac{2\bar{h}^2}{e^{*2}}, \quad if \quad 0 \le 2\bar{h} < e^*, \\ \dfrac{2(e^* - \bar{h})^2}{e^{*2}}, \quad if \quad e^* \le 2\bar{h} < 2e^* \\ 0, \quad if \quad 2\bar{h} \ge 2e^*. \end{array} \right\} \tag{23}$$

Given the efficient effort levels induced by the optimally designed policy, the relative magnitude of probabilities of violation under individual quotas and collective quotas is as follows:[16]

(a) When $0 < \bar{h} < 0.5e^*$, $\Pr(h_i^* > \bar{h}) < \Pr(h_1^* + h_2^* > 2\bar{h})$.

(b) When $\bar{h} = 0.5e^*$, $\Pr(h_i^* > \bar{h}) = \Pr(h_1^* + h_2^* > 2\bar{h})$.

(c) When $0.5e^* < \bar{h} < e^*$, $\Pr(h_i^* > \bar{h}) > \Pr(h_1^* + h_2^* > 2\bar{h})$.

(d) When $\bar{h} \ge e^*$, $\Pr(h_i^* > \bar{h}) = \Pr(h_1^* + h_2^* > 2\bar{h}) = 0$.

This yields the following conclusion:

Result 1: *In a stochastic world, for the given efficient effort levels by both harvesters, the relative magnitudes of the probability of violating the individual limit and the collective limit depends on* $\bar{h}$. *For* $\bar{h} < e^*$, *the probability of violating the individual limit is greater than the probability of violating the*

[16] Note that these rankings, Result 1 and the discussion of Figure1 also hold for general symmetric effort level e, and can be further extended to cases with asymmetric effort levels.

collective limit when $\bar{h}$ is high. Conversely, the collective limit is more likely to be violated than the individual limits when $\bar{h}$ is low.

We can use Figure1 to explain the basic idea of Result 1. The red curve in Figure 1 is the cdf of the summation of the two uniform distributions, denoted $F_1(x)$, i.e., the cdf under the collective quota. The black solid straight line denotes the cdf of one uniform distribution, denoted $F_2(x)$, i.e., the cdf under the individual quotas. The blue dotted straight line is a pseudo-cdf line, which doubles each horizontal ordinate of the cdf of one uniform distribution while keeps its corresponding vertical ordinate unchanged, denoted as $F_3(x)$. For $0 \le \bar{h} < 0.5e^*$, i.e., $0 \le 2\bar{h} < e^*$ (e.g., $\bar{h}_1$ in the graph), we have $\Pr(h_i^* > \bar{h}) = |AB| < |EF| = \Pr(h_1^* + h_2^* > 2\bar{h})$, where $|\cdot|$ denotes the distance between two points. Similarly, for $0.5e^* < \bar{h} < e^*$, i.e., $e^* < 2\bar{h} < 2e^*$ (e.g., $\bar{h}_2$ in the graph), we have $\Pr(h_i^* > \bar{h}) = |CD| > |GH| = \Pr(h_1^* + h_2^* > 2\bar{h})$. At $\bar{h} = 0.5e^*$, i.e., $2\bar{h} = e^*$, $\Pr(h_i^* > \bar{h}) = \Pr(h_1^* + h_2^* > 2\bar{h})$.

Result 1 implies that the probability that the individual quota will be exceeded is not necessarily larger than the probability that the collective limit will be exceeded. It depends on the nature of the underlying distribution of harvests and the magnitude of the quotas. Here, for example, given that the individual harvest is uniformly distributed, the aggregate harvest has a triangular distribution, i.e., the pdf is an increasing function in the lower range and a decreasing function in the higher range. As a result, the corresponding cdf curve is convex in the lower range and concave in the higher range. This leads to the different relative magnitudes of the probabilities of violating the individual limit and the collective limit in different ranges. Under this specific uniform distribution, the ranking of probabilities of violating individual quota and collective quota is ambiguous. While we have not shown that the ranking

is ambiguous *for all* distributions, the ambiguity under the uniform distribution implies that it is not possible to get an unambiguous ranking for general distributions.[17]

4.2. Expected magnitudes of violation

Next we can rank the expected unconditional magnitude of violation (hereafter, expected magnitude of violation for short) under these four cases. Denote the expected magnitudes of violation, given the efficient efforts by

$M^I = E[(h_i^* - \bar{h}) \mid h_i^* > \bar{h}]\Pr(h_i^* > \bar{h})$, $M^P = E[(h_i^* - \bar{h}) \mid h_1^* + h_2^* > 2\bar{h}] * P(h_1^* + h_2^* > 2\bar{h})$, and

$M^N = M^S = E[(h_1^* + h_2^* - 2\bar{h}) \mid h_1^* + h_2^* > 2\bar{h}]\Pr(h_1^* + h_2^* > 2\bar{h})$, respectively. Comparing M^I, M^P, M^N and M^S gives the following result:

Proposition 5: *In a stochastic world, given the efficient effort levels by both harvesters, the ranking of the expected magnitude of violation under the four alternative policies depends on the quota* $\bar{h}$ *. More specifically,*

$$\begin{cases} M^I < M^P < M^S = M^N, & if \quad 0 < \bar{h} < 0.5e^*, \\ M^I < M^S = M^N < M^P, & if \quad 0.5e^* < \bar{h} < 5e^*/8, \\ M^S = M^N < M^I < M^P, & if \quad 5e^*/8 < \bar{h} < e^*. \end{cases}$$

[17] We can extend the analysis to more general cases where there are three or more identical harvesters. For the summation of three or more uniform distributions; the pdf also increases in the lower range and then declines in the upper range. Thus, the curve of the expected loss function would also be convex in the lower range and concave in the higher range. We can conclude that the introduction of more identical harvesters will not change the basic conclusions of Result 1.

Note that the ambiguous ranking of the expected magnitudes of violation results not only from the ambiguity of the probabilities of violation noted in the previous subsection, but also from the ambiguous ranking of the expected conditional magnitudes of violation.[18] The ambiguity in the ranking of the expected magnitudes of violation under individual limits without trading vs. collective limits is mainly due to the ambiguity of the probabilities of violation under these two kinds of constraints. However, the ambiguity in the probabilities of violation does not necessarily imply an ambiguous ranking in expected magnitude of violation, as shown in the comparison between individual limits with and without trading.

4.3. Optimal penalty rates

We first note that, when $\bar{h} = 0$, Propositions 1-4 imply that, to induce the first-best outcome, the regulator should set a Pigouvian tax rate (or equivalently, marginal penalty here) equal to the marginal social damage to internalize the social cost of the harvesters' behavior. That is, setting $k_I^* = k_P^* = 0.5k_N^* = k_S^* = d$, i.e., $k_I^* = k_P^* = k_S^* = d$ and $k_N^* = 2d$ induces the efficient effort. Thus, in the absence of a quota, all four policies simply reduce to a standard Pigouvian tax. However, since pure tax mechanisms are seldom (if ever) used in fisheries management and our interest is in rights-based policies that allocate quota, we focus on the case where $\bar{h} > 0$.

To compare the optimal penalties when $\bar{h} > 0$, note that, for any given policy parameters $(k, \bar{h})$, the harvesters or the group choose the privately optimal effort level where the private marginal benefit

[18] Specifically, define $G^I = E[(h_i^* - \bar{h}) \mid h_i^* > \bar{h}]$, $G^P = E[(h_i^* - \bar{h}) \mid h_1^* + h_2^* > 2\bar{h}]$, and $G^N = G^S = E[(h_1^* + h_2^* - 2\bar{h}) \mid h_1^* + h_2^* > 2\bar{h}]$ as the expected conditional magnitudes of violation, given optimal effort. Then we have

$$\begin{cases} G^P < G^I < G^S = G^N, & if \quad 0 < \bar{h} < (6+\sqrt{6})e^*/10, \\ G^I < G^P < G^S = G^N, & if \quad (6+\sqrt{6})e^*/10 < \bar{h} < 0.5e^*, \\ G^I < G^S = G^N < G^P, & if \quad 0.5e^* < \bar{h} < e^*. \end{cases}$$

equals private marginal cost. This effort level is a function of $(k,\bar{h})$, denoted as $\tilde{e}_i^J(k,\bar{h})$, where $J = I,P,S,N$ for four scenarios, respectively. For simplicity, we drop the index i, i.e., we use $\tilde{e}^J(k,\bar{h})$ to denote each harvester's choice of effort when faced with any given $(k,\bar{h})$ combination. When $\bar{h} > 0$, we can easily prove that under all four policies $\tilde{e}^J(k,\bar{h})$ is monotonically decreasing in *k* and monotonically increasing in $\bar{h}$. Figure 2 shows the relative position of four $\tilde{e}^J(k,\bar{h})$ curves $(J = I,P,S,N)$ for a given $\bar{h}$. Drawing a horizontal line $\tilde{e}(k) = e^*$ that insects the four curves, we can depict the optimal penalty rates, i.e., the rates that induce the efficient level of effort. Comparing the optimal penalty rates gives the following result:

Proposition 6: *In a stochastic world, to induce the efficient effort, the ranking of optimal penalty rates under four alternative policies depends on the quota* $\bar{h}$. *More specifically,*

$$\begin{cases} d < k_S^* < k_I^* < k_P^* < k_N^*, & if \quad 0 < \bar{h} < 3e^*/8, \\ d < k_I^* < k_S^* < k_P^* < k_N^*, & if \quad 3e^*/8 < \bar{h} < 0.5e^*, \\ d < k_I^* < k_P^* < k_S^* < k_N^*, & if \quad 0.5e^* < \bar{h} < e^*. \end{cases}$$

Figure 2 illustrates the middle case where $3e^*/8 < \bar{h} < 0.5e^*$, under which $d < k_I^* < k_S^* < k_P^* < k_N^*$. In general, when $\bar{h} > 0$, the marginal penalty will be discounted by the probability that the quota is exceeded. Therefore, the regulator has to impose a penalty rate higher than the marginal social damage to induce the efficient effort, i.e., $k_I^*, k_P^*, k_S^*, k_N^* > d$. In addition, because private marginal benefits are the same across these four cases, i.e., $MB(e_i) = 0.5 - 2e_i$, optimal penalty rates should be adjusted to reflect the differences in the expected marginal magnitude of violation (i.e., $\partial M^J / \partial e_i$, $J = I,P,S,N$) so that

$MC(e_i) = k*(\partial M^J / \partial e_i)$ are equal under four alternatives.[19] The intuition for the differing rates is discussion in more detail in Section 5. Before turning to that discussion, we note the implications of the above results for the distributional impacts of the four policies.

4.4. Expected net profits

Even though the optimal k^*'s adjust to reflect the differences in the marginal expected magnitude of violation, they are not adjusted to offset the differences in the expected magnitude of violation, i.e., the result is still a difference in expected penalties and hence expected net profits. Combining results from subsections 4.2 and 4.3 yields the following conclusions on how the four policies affect expected penalties and hence expected net profit:

Proposition 7: *In a stochastic world, for optimally designed policies, the collective limit with collective decisions yields the lowest expected penalty, followed by the individual limits without trading. However, whether the individual limit with trading or the collective limit with individual decisions leads to the highest expected penalty depends on the quota* $\bar{h}$ *. More specifically,*

$$\begin{cases} E[\Phi_i^N] > E[TC_i^P] > E[\Phi_i^I] > E[\Phi_i^S], & if \quad 0 < \bar{h} < 0.5e^*, \\ E[TC_i^P] > E[\Phi_i^N] > E[\Phi_i^I] > E[\Phi_i^S], & if \quad 0.5e^* < \bar{h} < e^*. \end{cases}$$

In terms of expected profits, this implies:

$$\begin{cases} E[\pi_i^N] < E[\pi_i^P] < E[\pi_i^I] < E[\pi_i^S], & if \quad 0 < \bar{h} < 0.5e^*, \\ E[\pi_i^P] < E[\pi_i^N] < E[\pi_i^I] < E[\pi_i^S], & if \quad 0.5e^* < \bar{h} < e^*, \end{cases}$$

[19] Furthermore, the k^*'s are increasing in $\bar{h}$ and k^*'s $\rightarrow \infty$ when $\bar{h} \rightarrow e^*$.

when effort levels are efficient for both harvesters.

Section 5 discusses the intuition underlying the different distributional effects of the policies.

5. Discussion

The differences in the expected penalties and hence expected profits under the four policies reflect the different incentives created by these policies. These differences stem from one or more of the following: moral hazard, risk pooling, and/or sharing risk through quota trading. To understand the role of each of these, in this section we highlight pairwise comparisons in which the scenarios differ with respect to only one of these.

5.1. Role of moral hazard

We can study the effect of moral hazard by comparing collective quotas with individual decisions to collective quotas with collective decisions. The main difference between these two scenarios is that the collective limit with individual decisions generates moral hazard. A collective limit with collective decisions operates as if there is a single owner who coordinates the harvest activity among all the vessels to optimize the overall outcome for the group as a whole. There is no moral hazard problem in this scenario, i.e., no incentive to "shirk", since the impacts of shirking are fully internalized. In contrast, under a collective limit with individual decisions, each harvester wants to maximize his own profit. The harvesters interact with each other through the group limit. Since each harvester will reap the full benefit from additional harvest that exceeds the group quota while only paying a fraction of the associated penalty, each faces an incentive to "over-fish", which creates a moral hazard problem.

More specifically, recall from Proposition 6 that, for a given quota $\bar{h}$, a collective limit with individual decisions should impose a higher optimal penalty rate than a collective limit with collective

decisions. It is easily shown that the optimal k^* under a collective limit with individual decisions is twice as large as that under a collective limit with collective decisions, i.e., $k_N^* = 2k_S^*$. In other words, because of the moral hazard problem, the regulator must set a higher penalty when decisions are made individually than when they are made collectively. Intuitively, under the collective limit with collective decisions, the group will coordinate the harvest activity across harvesters to maximize the overall expected net profits. In contrast, under the collective limit with individual decisions, each harvester in the pool wants to maximize individual profit. Increasing its effort level will raise the probability that the collective limit will be violated and hence the probability that the each member in the group will incur the penalty. However, the harvester ignores the negative externality of his behavior on others when he makes his own decision. Because the limits are set on the whole group, they will not be punished for violating individual limits. In order to keep the effort at the efficient level, the regulator has to set a higher optimal k^* to offset the negative effect of moral hazard under the collective limit with individual decisions.[20]

Given the efficient effort levels by both harvesters, the expected magnitudes of violation are the same, as shown in Proposition 5. Therefore, $E[\Phi_i^N] = 2E[\Phi_i^S]$, given $k_N^* = 2k_S^*$. Thus, the moral hazard problem reduces the industry-level expected net profits under collective limits. In contrast to the typical effect of moral hazard, here moral hazard under individual decisions does not affect social welfare, given the optimally designed policies. Nevertheless, it does hurt harvesters by imposing a higher optimal penalty rate and hence increasing the total expected penalty. That is, the regulator can design the optimal policies to induce the first-best outcome even with moral hazard problem. However, the moral

[20] This result is similar to that in Segerson's (1988) non-point source pollution model where firms face an industry-wide cutoff level for ambient quality.

hazard problem has negative distributional impacts on harvesters in the sense of reducing the expected net profit for the industry under the collective policies.

5.2. Role of risk pooling

We can see the role of risk pooling by comparing individual limits without trading to collective limits with collective decisions. There is no moral hazard in either case. As mentioned above, when the quota $\bar{h}$ is positive, the marginal penalty will be discounted by the probabilities that the quota is exceeded. Therefore, regulators should adjust the optimal penalty rates to reflect the differences in the expected marginal magnitude of violation, which depends on whether the difference in probabilities of violation or that in expected conditional magnitudes of violation dominates. We can show that the individual limit with trading has a lower expected marginal magnitude of violation than the collective limit with collective decisions when the quota is low and a higher expected marginal magnitude of violation when the quota is high. Therefore, compared to the collective limits with collective decisions, regulators need to impose a higher k^* when $\bar{h}$ is low and a lower k^* when $\bar{h}$ is high under the individual limit in the absence of trading.

However, the optimal penalty rates are not set to offset the differences in the expected magnitude of violation. Recall that given optimal policies, the expected total penalty is always lower under the collective limit with collective decisions than under the individual limits without a trade, i.e., $E[\Phi^S] < E[\Phi^I]$. That is, in the absence of trading, optimally designed collective limits with collective decisions yield higher industry-level expected net profits than optimally designed individual limits. Intuitively, the collective limit provides harvesters a mechanism for pooling risk. Given the efficient effort levels, the actual harvests under these two kinds of limits might be different due to the stochasticity of harvest. A collective limit allows for “smoothing” across the harvesters, balancing the

bad outcomes with good outcomes, which makes the overall expected penalty under the collective limit less than the sum of the individual expected penalties under individual limits. This, in turn, yields higher expected total net profits. In other words, the risk pooling mechanism does not mean a lower probability of suffering a penalty, but rather a lower expected penalty under collective limits.

Since the two policies we compare here differ only in terms of risk pooling, i.e., there is no moral hazard or quota trading under either, the above conclusions suggest that risk pooling by itself does not have efficiency implications (provided regulators adjust policy parameters optimally), but it does affect the total expected costs borne by harvesters. In particular, even though the probability of violating a collective limit is not necessarily less than the probability of violating individual limits, the expected total penalty is lower. Thus, since both policies yield efficient effort, regulators who seek to both induce efficient effort and reduce the negative impact of harvest restrictions on harvesters should prefer collective limits to individual limits when the collective will make collective decisions (thereby eliminating any moral hazard).

5.3. Role of quota trading

Comparing the individual limits with and without a trading market illustrates the impact of trading, which is a combination of two effects: risk spreading and moral hazard. Specifically, the trading price is capped by the penalty rate (or deemed value/safety valve), which will be reached when the collective quota is exceeded. In other words, the expected total expenditure on quota trading and penalties depends on the probability that the aggregate realized harvest exceeds the total issued quota, rather than the probability of violating the individual limit. On the one hand, this provides harvesters with a mechanism for risk sharing. However, on the other hand, it creates a moral hazard problem, similar to that under the collective limit with individual decisions.

Nonetheless, we can show that the individual limits with trading always have lower expected marginal magnitude of violation than the individual limits without trading. Therefore, the regulator should set k^* higher under individual limits with trading than without. Intuitively, this is because trading can smooth outcomes across harvesters and provide a mechanism for risk sharing in the sense that no one will be fined as long as the total realized harvest does not exceed the collective quota. This risk sharing opportunity creates an incentive for greater effort by harvesters. As a result, the regulator needs to impose a higher optimal penalty rate to offset the negative effect of moral hazard under trading.

Note that although both individual limits with trading and a collective limit with individual decisions generate a type of moral hazard problem, they are not exactly the same. Under the individual limits with trading, the expected penalties (plus spending in the trading market) are affected by the choice of others through the influence on the probability of violating the collective quotas. In contrast, under the collective limit with individual decisions, the expected penalties are affected by the choice of others not only through the effect on the probability of violating the group limit but also through the influence on the magnitude of violation. In other words, under the collective limit with individual decisions, the conditional penalty depends on the magnitude of aggregate violation, while under individual limits with trading, the penalty is based on the magnitude of a harvester's own violation. As a result, the incentive to increase effort is greater and hence the regulator has to impose a higher optimal k^* under the collective limit with individual decisions than under individual limits with trading, i.e., $k_N^* > k_P^*$.

Recall that in section 4.3, the expected magnitude of violation is always lower under individual limits without trading than with trading. Combining the impacts of optimal penalty rates and expected magnitude of violation, the total expected spending on trading and penalties under individual limits with

a quota market is always greater than the expected penalties under individual limits without trading. That is, trading reduces the industry-level expected net profits under individual limits, given the optimally designed policies. In other words, the advantage of trading as a mechanism for risk sharing is dominated by the negative impact of moral hazard.

In summary, in contrast to standard results for permit trading, given the optimally designed policies, here social welfare is the same with and without quota trading. However, the quota market actually makes harvesters worse off rather than better off. That is, due to the moral hazard problem, when regulators adjust the policy parameters optimally, the quota market reduces the industry-wide expected net profits under individual limits and thus has a negative distributional impact on harvesters.

6. Conclusion

In this paper, we compare collective quotas to individual quotas with and without permit markets. Specifically, we consider four alternative policies: (1) individual limits without a quota market (IFQs), (2) individual limits with a quota market (ITQs), (3) a collective limit with individual decisions, and (4) a collective limit with collective decisions. We find that the optimally designed policies can yield the first best under all four of these alternatives. Thus, if regulators adjust penalties optimally, there is no efficiency basis for preferring one policy approach over the others.

However, the expected net profit for the industry is not the same because the optimal expected penalty is not the same under the different policies. The difference in industry-level expected net profit is a distributional issue, rather than an efficient issue. Regulators typically care not only about efficiency but also about distributional impacts. We find that the moral hazard problem that arises under the collective limit with individual decisions makes harvesters worse off. Thus, moral hazard has a distributional (but not an efficiency) impact. In the absence of trading and moral hazard, as a result of

risk pooling, the collective limit with collective decisions yields higher expected profits than the individual limits. Finally, although the quota market provides an opportunity for risk spreading for harvesters, the potential moral hazard problem leads to a detrimental distributional impact on harvesters under trading. This is in contrast to the standard result that allowing permits to be traded makes firms better off.

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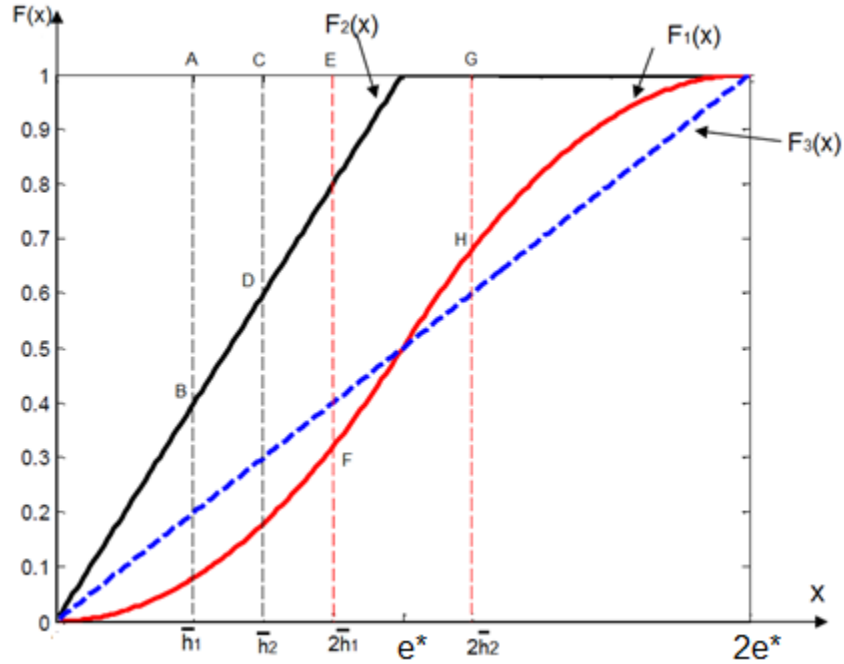
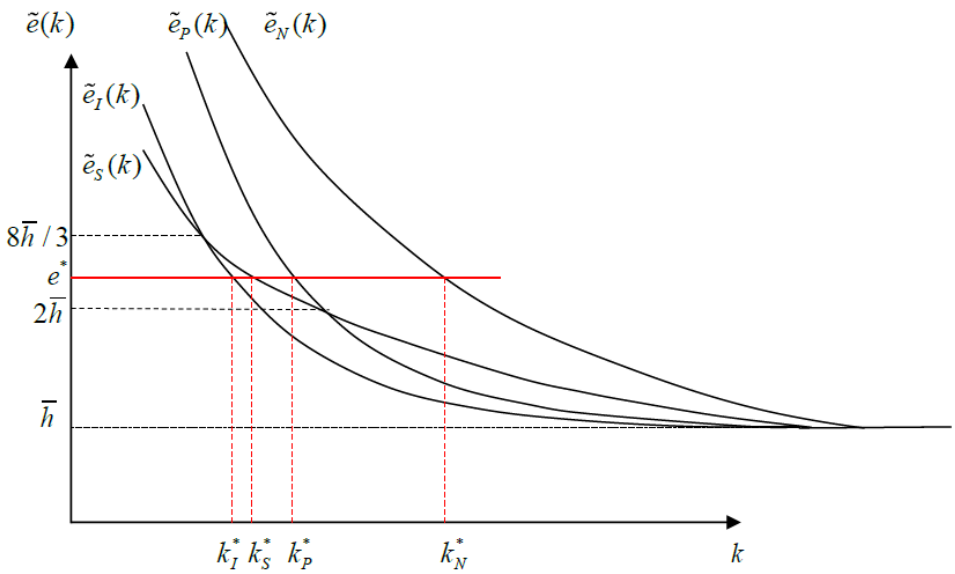
Fig.1. Comparison of probabilities of violation



If $0 < \bar{h} < 0.5e^*$ (e.g., $\bar{h}_1$ in the graph), then $\Pr(h_i > \bar{h}) = |AB| < |EF| = \Pr(h_1 + h_2 > 2\bar{h})$.

If $0.5e^* < \bar{h} < e^*$ (e.g., $\bar{h}_2$ in the graph), then $\Pr(h_i > \bar{h}) = |CD| > |GH| = \Pr(h_1 + h_2 > 2\bar{h})$.

Fig.2. Comparison of the optimal k^* under four policies



This graph shows the case where $2\bar{h} < e^* < 8\bar{h}/3$ (or equivalently, $3e^*/8 < \bar{h} < 0.5e^*$), which implies $k_I^* < k_S^* < k_P^* < k_N^*$.