Individual vs. Collective Quotas in Fisheries Management
Under Uncertainty

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Abstract: Rights-based approaches (e.g., ITQs, TURFs, collectives/cooperatives) are increasingly popular throughout the world, but there is relatively little theoretical literature comparing individual vs. collective approaches. This paper presents a stylized model that allows for such a comparison in a context where there is harvest uncertainty (and hence the potential for risk sharing) as well as potential moral hazard. The model is used to compare four alternative rights-based scenarios, two individual and two collective. A key feature of the model is the inclusion of a mechanism for paying penalties or buying additional quota when harvests exceed allowances (similar to a “deemed value” system), where the regulator can set the penalty or price. Contrary to what might be expected, the results imply that all four scenarios can yield first best effort levels. However, they have quite different distributional impacts. Because the structure of the underlying incentives differ across the scenarios, the regulator must set the penalty/price at a different level to induce first best effort choices, and these different penalties/prices, as well as the different conditions that trigger them, in turn imply different expected total costs for harvesters. Thus, in this context the choice between individual and collective approaches comes down to a distributional rather than an efficiency comparison.

Key words: collective limits, risk pooling, moral hazard, quota trading, fisheries management

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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 (Annala, 1996; Arnason, 2012; Copes, 1986; Grafton, 1996; Sanchirico et al., 2006; Squires et al., 1995). As an alternative to approaches based on granting rights to individual harvesters 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) (Cancino et al., 2007; Deacon, 2012; Holland, 2004; Segerson, 2014; Uchida and Makino, 2008; Wilen et al., 2012). 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 (Baland and Platteau, 2003).

Often, a collective property right is created through a collective limit on the harvest of a target species or bycatch imposed by regulators or fishery managers (Abbott and Wilen, 2009; Bonzon et al., 2013; Deacon, 2012; Segerson, 2011). For example, a recent survey by Ovando et al. (2013) found that approximately 50% of the fishing cooperatives surveyed faced a government-imposed total allowable catch (TAC). Furthermore, Bonzon et al. (2013) find that about 10% of catch share programs allocate allowable catch to a group. Collective limits or quotas typically seek to limit fishing activity either to reduce intra-fishery externalities stemming from the common property nature of the resource or to reduce externalities borne outside the fishery, stemming, for example, from bycatch of other (sometimes endangered) species, ecological impacts or habitat degradation from disruptive fishing, or impacts on 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, a harvest (or bycatch) allocation is assigned to the group as a whole, which is then free to determine how it will operate under that collective limit. Regardless of the rules of operation, use of part of the collective quota by one harvester means that less is available for use by
others, which implies that the opportunities available to one harvester are impacted by the harvesting behavior of others.

A key question for fisheries managers seeking to assign property rights to limit harvests is whether to assign rights to individuals or collectives. The advantages and disadvantages of the use of individual rights, in particular ITQs, relative to traditional regulation of inputs or effort have been widely recognized in the literature. The incentive effects of collective quotas have been studied far less. Nonetheless, arguments have been made for and against the use of collective limits. For example, a collective assignment of rights can provide an incentive for members of the group to reduce intra-group externalities (Criddle and Macinko, 2000; Deacon et al., 2008). However, depending on how decisions within the group are made, collective quotas can 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 where individual harvesters still control when and how much they fish, if they cannot be accountable for past overfishing, harvesters have an incentive to ‘race-to-fish’ if the fishing season will be closed once the aggregate limits are reached (Copes, 1986; Pascoe et al., 2010; Yagi et al., 2012; Bonzon et al. 2013). The common pool structure created by the collective limit can cause 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). It is often argued that the moral hazard problem is more serious for large pools with heterogeneous fishermen and asymmetric information (Holland, 2010; Holland and Jannot, 2012). Furthermore, collective quotas often involve a pooling of revenues. Ovando et al. (2013) found that 47% of the fishing cooperatives surveyed have some form of income pooling. This might also create an incentive to shirk and free ride on the efforts of others (Uchida and Baba, 2008; Uchida and Watanobe, 2008). The ability to free-ride depends crucially on the extent to which effort decisions for individual harvesters are made cooperatively (for example, by a central governing committee) or non-cooperatively (i.e., individually by members of the group).

On the other hand, collective quotas have also been advocated as a mechanism for risk pooling in fisheries where payoffs to harvesters are stochastic. Holland (2010) finds that sharing quota through risk pools can help reduce financial risk when bycatch is highly uncertain. The potential benefits of pooling are usually described in terms of reducing the risk of income fluctuation by sharing input and maintenance costs (Platteau and Seki, 2001), or sharing revenue or profit (Deacon et al., 2008; Knapp, 2008; Soboil and Craig, 2008; Uchida and Baba, 2008). Information sharing among members in the pool can also dampen the impact of uncertainty (Deacon et al., 2008; Deacon, 2012; Soboil and Craig, 2008).
Although collective quotas provide a means of pooling risk, they are not the only mechanism that can be used for this purpose. For example, the transferability of individual quotas can also provide a mechanism for spreading risks across individual harvesters. The potential for trading quotas effectively allows harvesters to pool their quotas and redistribute the quota through trading in the market. Compared to non-transferable individual quotas, efficient quota markets can reduce the risk of income fluctuations for individual harvesters (Holland, 2010). Although there is surprisingly little discussion of the role of trading as a mechanism for spreading risk in fisheries, this role has been recognized more broadly in the literature on tradable emission permits. For example, Mrozek and Keeler (2004) note that markets for tradable emissions permits provide firms an opportunity to respond to uncertainty, because the permit market smooths the outcomes across firms, making the violation of the limit 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).

The above literature suggests the importance of two key issues that arise under collective quotas: moral hazard and the potential for risk pooling when outcomes are stochastic. Thus, a key question in deciding whether rights should be allocated with collective or individual quotas is whether, in the presence of these two issues, a collective quota will lead to efficient effort by individual harvesters, or at least to a more efficient outcome than individual quotas. However, to date, the theoretical literature on collective quotas has not considered this question. First, existing theoretical models of collective quotas in fisheries have not incorporated these two issues simultaneously. Models that incorporate moral hazard, such as Abbot and Wilen (2009) and Fell (2010), are deterministic and hence cannot evaluate the impact of collective quotas on risk pooling, while stochastic models of risk pooling, such as Holland (2010), do not explicitly model incentives and the associated moral hazard. Thus, the existing theoretical models cannot identify the extent to which these two features of collective quotas interact to affect efficiency.

Second, and as importantly for our purposes, the existing models assume that the fishery is closed once the collective quota is met. While this is perhaps the most common mechanism used in practice, it is not the only one available. An alternative is the use of economic incentives, e.g., subsidies, rewards, taxes or “deemed values” (Pascoe, 1997; Pascoe et al., 2010; Sanchirico, et al., 2006; Squires et al., 1995). For example, the deemed value system implemented in New Zealand allows harvesters to purchase additional quota to balance their over-quota catch (Holland, 2010; Pascoe, 1997; Pascoe et al., 2010; Peacey, 2002; Sanchirico, et al., 2006; Soboil and Craig, 2008; Squires et al., 1995). This is particularly useful when harvests are stochastic so that harvesters cannot
tightly control the amount they harvest at a given time. Deemed values can maintain the incentive to land, rather than discard over-quota catch (Holland and Herrera, 2006; Pascoe, 1997). Adjusting the deemed value rate in response to the exceeding amount can control the risk of overexploitation (Holland and Herrera, 2006). It is similar to the use of a “safety valve” in the context of cap-and-trade programs to reduce pollution, under which additional allowances (in excess of the cap) can be purchased at a specified safety valve price (Fell and Morgenstern, 2010; Jacoby and Ellerman, 2004; Metcalf, 2009; Murray et al., 2009). Hybrid policies (i.e., mixed price-quantity instruments) such as the safety valve have been shown to be more efficient than pure quantity instruments, such as permits, when there is uncertainty (Jacoby and Ellerman, 2004; Pizer, 2002; Roberts and Spence, 1976). A key advantage of this type of hybrid approach is that it allows a regulator to set the price of additional quota. Setting the price appropriately is a key determinant of the effectiveness of the policy in protecting fishery sustainability (Marchal et al., 2009; Pascoe et al., 2010), and is important to balance the tradeoff between the impacts on production and discarding (Squires et al., 1995). Weitzman (2002) theoretically shows that landing fees are superior to harvest quotas when ecological uncertainty exists. Thus, when evaluating the efficiency of collective quotas under uncertainty, rather than assuming a fishery closure or enforcement method that will typically be sub-optimal (as in previous studies, such as Abbott and Wilen, 2009; Fell, 2010; Holland, 2010; and Singh and Weninger, 2009), it is important to ask whether collective quotas would be efficient if regulators are able to optimally penalize overages or “sell” additional quota at an optimally set price.

The purpose of this paper is to evaluate the efficiency of collective quotas vs. individual quotas when both moral hazard and uncertainty are potentially important and regulators can optimally choose a price for additional quotas under the type of limit(s) they impose. We analyze four alternative policy scenarios: (1) individual limits without trading (hereafter, called “non-tradable quotas”), (2) individual limits with trading (i.e., ITQs), (3) collective quotas where effort choices are decentralized (hereafter, called “decentralized collectives”), and (4) collective quotas where effort choices are made collectively (hereafter, called “centralized collectives”). All four of these approaches have been used in fisheries management, as shown in Table 1. Rather than focusing on well-known common property issues that arise in fisheries, we focus instead on the scenario where a welfare-maximizing regulator uses quotas (either individual or collective) as a mechanism for limiting damages from fishing that are external to (current) harvesters. For each policy scenario, we assume that the regulator requires harvesters to buy additional quota to cover any overage and allow the regulator to set the corresponding quota price optimally.
We find that, when optimally designed, all four alternative policy scenarios can yield the first best (even in the presence of uncertainty and moral hazard). Thus, there is no efficiency basis for preferring one over the others. However, because the four alternatives create different harvesting incentives, the optimal quota prices as well as the conditions that trigger payment differ, which in turn leads to differences in individual and industry-wide expected net profits across the policy scenarios. This implies that, although the efficiency impacts are the same, the four scenarios have different distributional impacts.

Since regulators are typically concerned about the distributional as well as the efficiency impacts of policies, a key question is how these alternatives rank in terms of distributional impacts on harvesters, given the optimally designed policies. We find that, although the disincentives it creates can be corrected through optimally chosen prices, the moral hazard problem that arises under decentralized collectives makes harvesters worse off in terms of distributional impact, compared with centralized collectives. In addition, because of the benefits of risk spreading, ITQs yield a higher aggregate expected net profit than non-tradable quotas. Although both ITQs and centralized collectives provide mechanisms for risk sharing, centralized collectives hurt harvesters by requiring a higher optimal quota price and hence higher expenditure on additional quota. Thus, although both individual and collective quotas are equally efficient, when tradable, individual quotas can lead to a higher aggregate expected profit than collective quotas.

The paper is organized as follows. In Section 2, we present the basic model and the social planner’s problem and derive the first-best outcome. Section 3 analyzes the four policy scenarios. Section 4 discusses the incentives created by the alternative scenarios and hence their distributional impacts. We first compare the two individual quota scenarios, then the two collective quota scenarios, and finally individual quotas vs. collective quotas. Section 6 considers the extension to the cases with heterogeneous harvesters and Section 7 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 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 undertakes 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. 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 and risk pooling.

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 $\varepsilon_i$: $h_i = e_i F(\varepsilon_i)$, where $F(\varepsilon_i)=\phi e_i$ ($i=1,2$).

We assume the stochastic elements of the two harvesters are uncorrelated. This will be true if the location decision is made independently, the stock is randomly distributed throughout the fishing zone and there are no intra-fishery externalities. For simplicity, we assume $\phi=1$ and $\varepsilon_i$ 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 profit for harvester $i$ (exclusive of any policy-related payments) is $E[\pi(e_i,\varepsilon_i)] = pE(h_i) - C(e_i) = pE[e_i F(\varepsilon_i)] - C(e_i)$, where $C'(\cdot)>0, C''(\cdot)>0$. Here we assume $C(e_i) = e_i^2$ and the price is normalized to one. 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. 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). For simplicity, we assume a linear damage function, i.e., $D(X) = dX$, where $d < 1$.

The efficient effort level will maximize social welfare:

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

Given $d < 1$, this problem yields an interior solution:
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. When harvesters choose their effort levels, they do not consider the negative externalities imposed on society. Ignoring the marginal social cost of their behavior leads them to undertake too much effort. This reflects the classic externality problem (Pigou, 1924).

3. Market Equilibria and Optimal Policy Designs

We consider four alternative policy scenarios that have been adopted in fisheries management: (1) individual non-tradable quotas, (2) individual tradable quotas (ITQs), (3) decentralized collectives, and (4) centralized collectives. We assume that harvesters or groups have to purchase additional quota to cover their over-quota catch. As noted above, this is analogous to New Zealand’s deemed value system or the use of a safety valve in emission permit trading. It is also equivalent to imposing a penalty for exceeding quota, where the total penalty is proportional to the amount of the overage. For each scenario, we first characterize private decisions, conditional on the harvest limits and prices (penalties) for additional quota. This is similar to what is done in the literature when prices are treated as exogenously set (e.g., landing taxes in Singh and Weninger, 2009). Given these responses, we then let the regulator choose quota prices under the different scenarios to maximize social welfare. For each scenario, 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 (non-tradable quotas)

Assume the regulator allocates quota \( \bar{h} \) to each harvester and the quota is not tradable. The harvester incurs no additional charge if the harvest is no more than the quota. However, if the quota limit is exceeded, the harvester has to purchase additional quota at a price \( k \). The expected total payment is then given by:

\[
\Phi_i^n = \begin{cases} 
0, & \text{if } h_i \leq \bar{h}, \\
(k(h_i - \bar{h}) \text{ if } h_i > \bar{h}, 
\end{cases}
\]

for \( i = 1, 2 \).
where the superscript $N$ denotes the case of individual limits without trading (non-tradable quotas).

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 charge. Specifically, the optimization problem for harvester $i$ ($i = 1, 2$) is:

$$\max E[\pi(e_i, e_i)] - E[\Phi^N_i] = E[e_i F(e_i)] - C(e_i) - E[k(h_i - \bar{h}) | h_i > \bar{h}] \Pr(h_i > \bar{h})$$

$$= \begin{cases} 0.5e_i - e_i^2 - k(e_i - \bar{h})^2/2e_i, & \text{if } e_i > \bar{h}, \\ 0.5e_i - e_i^2, & \text{if } e_i \leq \bar{h}. \end{cases}$$  

(3)

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

$$\frac{dE[\pi(e_i, e_i)]}{de_i} - \frac{dE[\Phi^N_i]}{de_i} = 0.5 - 2e_i - 0.5k(1 - \bar{h}^2/l e_i^2) = 0.$$  

(4)

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

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 $\bar{h}$. In deriving the optimal quota price both here and throughout the remainder of the paper, we assume the regulator sets the quota such that $\bar{h} < e^*$, i.e., the quota is less than the maximum possible harvest when effort is efficient. This implies that the quota has a positive probability of being binding even if harvesters choose efficient effort. Comparing the first order conditions in this scenario with those for the social planner’s problem, we have the following result (see the Supplemental Appendix for proofs of all results and propositions):

**Proposition 1.** Under non-tradable quotas, by setting $\bar{h}$ at any level smaller than $e^*$ and setting $k^*_N = \left(\frac{e^*}{e^* - \bar{h}}\right)d$, the regulator can induce the efficient effort levels by both harvesters.  

Proposition 1 shows that, even when harvest is stochastic, the regulator can induce the first best effort levels by adjusting the quota price $k$ (for a given quota $\bar{h}$) to internalize the expected social cost of the harvesters’ behavior. We discuss the optimal price 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 quotas 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 trade. We assume the regulator can observe the realized harvests and trading amounts. The regulator requires harvester \( i \) to purchase additional quota at a price \( k \) if his harvest exceeds the amount of quota he holds. That is,

\[
\Phi^T_i = \begin{cases} 
0, & \text{if } h_i \leq \bar{h} + t_i, \\
\frac{k}{(h_i - \bar{h} + t_i)}, & \text{if } h_i > \bar{h} + t_i,
\end{cases}
\]

where \( t_i \) is the quantity of quota purchased from (if it is positive) or sold to (if it is negative) the other harvester, and \( (\bar{h} + t_i) \) is the total quantity held by harvester \( i \). The superscript \( T \) denotes the case of ITQs.

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 \((TC_i^T)\), given the quota market and the price charged by the regulator. He makes choices based on the realized harvests, so there is no uncertainty in the second period. Harvester \( i \)'s problem is then:

\[
\min_{h_i} TC_i^T = \Phi_i^T + t_i r
\]

\[
= \begin{cases} 
rt_i, & \text{if } h_i \leq \bar{h} + t_i, \\
k(h_i - \bar{h} - t_i) + rt_i = (r-k)t_i + k(h_i - \bar{h}), & \text{if } h_i > \bar{h} + t_i,
\end{cases}
\]

where \( r \) is the per unit quota price in the trading market, which is endogenously determined by supply and demand for quota.\(^{19}\) 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 price charged by the regulator, \( k \). The decision to trade 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 charge \( k \), while the marginal cost is the quota trading price \( r \). Thus, the total costs in the second period will be given by:

\[
TC^T_i = r(h_i - \bar{h}),
\]

(7)

where

\[
\begin{align*}
    r &= 0, & \text{if } h_i + h_2 < 2\bar{h}, \\
    r &= k, & \text{if } h_i + h_2 > 2\bar{h}, \\
    0 &\leq r \leq k, & \text{if } h_i + h_2 = 2\bar{h}.
\end{align*}
\]

Anticipating the expected outcome in the second period (and ignoring any discounting, since both periods occur within a given season), 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 any payment to the regulator):

\[
\max_{e_i} E[\pi(e_i, e_i)] - E[TC^T_i] = 0.5e_i - e_i^2 - E[TC^T_i],
\]

(8)

where \( E[TC^T_i] \) is the first period expectation of the total costs from trading and charges in the second period, given by

\[
E[TC^T_i] = P(h_i + h_2 > 2\bar{h}) \times E[TC_i | h_i + h_2 > 2\bar{h}]
\]

\[
= P(h_i + h_2 > 2\bar{h}) \times E[k(h_i - \bar{h}) | h_i + h_2 > 2\bar{h}].
\]

(9)

Assuming the two harvesters have full knowledge of the cost functions of the other firm, a Nash equilibrium \( e^T_i \) \((i = 1, 2)\) satisfies the following first order conditions:

\[
\frac{\partial E[\pi(e_i, e_i)]}{\partial e_i} - \frac{\partial E[TC^T_i]}{\partial e_i} = 0.5 - 2e_i - \frac{\partial \{P(h_i + h_2 > 2\bar{h}) \times E[k(h_i - \bar{h}) | h_i + h_2 > 2\bar{h}]\}}{\partial e_i} = 0,
\]

(10)

for \( i = 1, 2 \). Thus, the optimal effort is at the point where the marginal benefit from increased expected pre-charge profits equals the marginal cost from increased expected total spending on quota trading and charges. Given identical harvesters, we will focus on symmetric, pure strategy Nash equilibria, similar to Abbott and Wilen (2009), where \( e_1 = e_2 \).

Comparing the first order conditions under ITQs with those for the social planner’s problem, we have the following conclusion:
Proposition 2. Under ITQs, by setting $\bar{h}$ at any level smaller than $e^*$, and setting

$$k^*_r = \begin{cases} 
\frac{3e^3d}{(3e^3 - 4h^*)}, & \text{if } 0 < \bar{h} < 0.5e^*, \\
\frac{3e^3d}{4(e^* - \bar{h})(2e^* + \bar{h})}, & \text{if } 0.5e^* \leq \bar{h} < e^*,
\end{cases}$$

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

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

3.3 Decentralized effort control under collective quotas (“decentralized collectives”)

Instead of distributing the quota to individual harvesters, it is also possible to allocate a collective quota, i.e., total allowable catch (TAC), to a group as a whole. In this case, the members in the group will need to buy additional quota 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. We assume first that each member within the group makes his own decision independently. However, if the collective quota is violated, the collective will have to buy additional quota at a total cost of $k(h_1 + h_2 - 2\bar{h})$. We assume that this total charge is shared equally by the harvesters. Thus, the charge for harvester $i$ ($i = 1, 2$) is given by:

$$\Phi^D_i = \begin{cases} 
0, & \text{if } h_1 + h_2 \leq 2\bar{h}, \\
0.5k(h_1 + h_2 - 2\bar{h}), & \text{if } h_1 + h_2 > 2\bar{h},
\end{cases}$$

where the superscript $D$ denotes the case of decentralized collectives.

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

$$\max_{\varepsilon_i} E[\pi(e_j, \varepsilon_i)] - E[\Phi^D_i]$$

$$= 0.5e_i - e_i^2 - E[0.5k(h_1 + h_2 - 2\bar{h}) | h_1 + h_2 > 2\bar{h}] \times \Pr(h_1 + h_2 > 2\bar{h})].$$

(12)

The necessary conditions for a Nash equilibrium are:

$$\frac{\partial E[\pi(e_j, \varepsilon_i)]}{\partial e_i} - \frac{\partial E[\Phi^D_i]}{\partial e_i} = 0.5 - 2e_i - 0.5k \frac{\partial E[(h_1 + h_2 - 2\bar{h}) | h_1 + h_2 > 2\bar{h}] \times \Pr(h_1 + h_2 > 2\bar{h})]}{\partial e_i} = 0, \quad (13)$$

(13)
for \( i = 1, 2 \). For each harvester, the optimal effort is at the point where the marginal benefit from increased expected pre-charge profits equals the marginal cost from increased expected charges, given the effort level of the other harvester. As in the case of ITQs, we will focus on symmetric, pure strategy Nash equilibria.

Comparing the first order conditions in (13) with those for the social planner’s problem, we have the following conclusion:

**Proposition 3.** Under decentralized collectives, by setting \( h \) at any level smaller than \( e^* \), and setting

\[
k^*_D = \begin{cases} 
\frac{6e^*d}{(3e^* - 8h^*)}, & \text{if } 0 < h < 0.5e^*, \\
\frac{3e^*d}{2(e^* - h^*)^2(e^* + 2h^*)}, & \text{if } 0.5e^* \leq h < e^*,
\end{cases}
\]

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, the regulator can still set the quota price to induce the first best effort levels.

### 3.4 Centralized effort control under collective quotas (“centralized collectives”)

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 need to purchase additional quota at a per-unit price \( k \). That is, the aggregate charge for the group is given by:

\[
\Phi^C = \begin{cases} 
0, & \text{if } h_1 + h_2 \leq 2 \overline{h}, \\
k(h_1 + h_2 - 2 \overline{h}), & \text{if } h_1 + h_2 > 2 \overline{h},
\end{cases}
\]

where the superscript \( C \) denotes the case of centralized collectives. This is comparable to the total cost of quota under the decentralized collective.

The problem for the whole group is:

\[
\max_{e_1, e_2} \sum_{i=1}^{2} E[\pi(e_i, e_{-i})] - E[\Phi^C]
\]

\[
= (0.5e_1 - e_1^2 + 0.5e_2 - e_2^2) - E[k(h_1 + h_2 - 2 \overline{h}) | h_1 + h_2 > 2 \overline{h}] \times \Pr(h_1 + h_2 > 2 \overline{h}).
\]

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

\[
\frac{\partial}{\partial e_i} \sum_{i=1}^{2} E[\pi(e_i, e_{-i})] - \frac{\partial E[\Phi^C]}{\partial e_i} = 0.5 - 2e_i - k \frac{\partial E[(h_1 + h_2 - 2 \overline{h}) | h_1 + h_2 > 2 \overline{h}] \times \Pr(h_1 + h_2 > 2 \overline{h})}{\partial e_i} = 0,
\]

\( i = 1, 2 \).
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 centralized collectives, by setting $\bar{h}$ at any level smaller than $e^*$, and setting

$$k_c^* = \begin{cases} 
\frac{3e^*d}{(3e^* - \bar{h})^3}, & \text{if } 0 < \bar{h} < 0.5e^*, \\
\frac{3e^*d}{4(e^* - \bar{h})^2(e^* + 2\bar{h})}, & \text{if } 0.5e^* \leq \bar{h} < e^*,
\end{cases}$$

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

Proposition 4 shows that, with the appropriate adjustment in the charge for additional quota, the regulator can induce efficiency effort levels for any $\bar{h} < e^*$ under centralized collectives.

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 charge here) equal to the marginal social damage to internalize the social cost of the harvesters’ behavior. That is, when $\bar{h} = 0$, setting $k_N^* = k_T^* = k_C^* = d$ and $k_D^* = 2d$ induces the efficient effort. Thus, in the absence of a quota, all four policy scenarios simply reduce to imposing a standard Pigouvian tax. When $\bar{h} = 0$, the ranking of expected charge per harvester is $E[\Phi_N^i] = E[TC_i^T] = E[\Phi_C^i] = 0.5E[\Phi_D^i]$, where $E[\Phi_N^i] = E[\Phi_C^i] = E[\Phi_D^i] / 2$. Therefore, the ranking of expected net profit per harvester is $E[\pi_N^i] = E[\pi_T^i] = E[\pi_C^i] > E[\pi_D^i]$.

However, since pure tax mechanisms are seldom (if ever) used in fisheries management and our interest is in rights-based policy scenarios that allocate quota, we focus on the case where $\bar{h} > 0$. To compare the optimal quota prices 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 equals private marginal cost. This effort level is a function of $(k, \bar{h})$, denoted as $\hat{e}_{i,j}(k, \bar{h})$, where $j = N, T, D, C$ for the four scenarios, respectively. For simplicity, we drop the index $i$, i.e., we use $\hat{e}_j(k, \bar{h})$ to denote each harvester’s choice of effort when faced with any given $(k, \bar{h})$ combination under scenario $j$. When $\bar{h} > 0$, we can easily prove that under all four policy scenarios, $\hat{e}_j(k, \bar{h})$ is monotonically decreasing in $k$ and monotonically increasing in $\bar{h}$. Figure 1 illustrates an example of
the relative positions of the four $\partial_j(k, h)$ curves for a given $h$. By drawing a horizontal line at $e^*$ that insects the four curves, we can identify the optimal quota prices, i.e., the prices that induce the efficient level of effort. In general, when $h > 0$, the quota price (or equivalently, additional charge) will be weighted by the probability that the quota is exceeded, which is less than one. Therefore, the regulator has to impose a price higher than the marginal social damage to induce the efficient effort, i.e., $k^*_x, k^*_y, k^*_d, k^*_c > d$. We will compare these optimal prices in more detail in Section 4.

In summary, as long as the charges for additional quota are set appropriately given $h$, all four policy scenarios 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 scenario over the other. Nonetheless, when optimally designed, these scenarios 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 quota prices are different. As a result, the expected charge 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, stemming from the differing incentives created by the alternatives. In the following section, we will compare the expected charges under these alternatives, and the implications for their distributional impacts on harvesters.

4. Comparing Distributional Impacts under Optimally Designed Policy Parameters

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

$$E[\Phi_i^N] = k^*_x \times E[(h_i^* - h) | h_i^* > h] \times Pr(h_i^* > h),$$  \hspace{1cm} (17)

$$E[TC_i^T] = k^*_y \times E[(h_i^* - h) | h_i^* + h_i^* > 2h] \times Pr(h_i^* + h_i^* > 2h),$$  \hspace{1cm} (18)

$$E[\Phi_i^D] = 0.5k^*_d \times E[(h_i^* + h_i^* - 2h) | h_i^* + h_i^* > 2h] \times Pr(h_i^* + h_i^* > 2h),$$  \hspace{1cm} (19)

$$E[\Phi_i^C] = E[\Phi_i^C]/2 = 0.5k^*_c \times E[(h_i^* + h_i^* - 2h) | h_i^* + h_i^* > 2h] \times Pr(h_i^* + h_i^* > 2h),$$  \hspace{1cm} (20)

where $h_i^* = \varepsilon_i e^*$, for $i = 1, 2$. Comparing (17)-(20) shows that the expected charges under the different policy scenarios will differ because of differences in the expected (unconditional) magnitude of the violations (which result from the differences in the probabilities of violation and conditional expected magnitudes of violation), and the prices of purchasing additional quota.
In this section, we compare the distributional impacts on harvesters, given optimally designed policy parameters. We first compare within the two categories, i.e., we compare the two individual quota policy scenarios (non-tradable quotas vs. ITQs), followed by the two collective quota scenarios (centralized collectives vs. decentralized collectives). We then compare across the categories, i.e., we compare the individual scenario with the highest expected profit to the collective scenario with the highest expected profit, to determine which scenario of the four yields highest expected profits.

4.1 Individual quotas: non-tradable quotas vs. ITQs

4.1.1 Probabilities of violation

Recall that, since $\varepsilon_i$ is uniformly distributed over $[0,1]$, $h_i^* = \varepsilon_i e^*$ is uniformly distributed over $[0,e^*]$. Thus, given $e^*$, the probability of violation under non-tradable quotas is:

$$\Pr(h_i^* > \bar{h}) = \begin{cases} 0, & \text{if } \bar{h} \geq e^*, \\ 1 - \frac{\bar{h}}{e^*}, & \text{if } 0 \leq \bar{h} < e^*. \end{cases} \quad (21)$$

Define $x = h_1^* + h_2^* = \varepsilon_1 e^* + \varepsilon_2 e^*$, which is the sum of two uniform distributions over $[0,e^*]$. The probability of violation under ITQs, given efficient effort levels, is then:

$$\Pr(h_1^* + h_2^* > 2\bar{h}) = \Pr(\varepsilon_1 e^* + \varepsilon_2 e^* > 2\bar{h}) = \begin{cases} 1 - \frac{2\bar{h}^2}{e^*}, & \text{if } 0 \leq 2\bar{h} < e^*, \\ \frac{2(e^* - \bar{h})^2}{e^*}, & \text{if } e^* \leq 2\bar{h} < 2e^*, \\ 0, & \text{if } 2\bar{h} \geq 2e^*. \end{cases} \quad (22)$$

Given the efficient effort levels induced by the optimally designed policy, the relative magnitudes of the probabilities of violation under individual quotas with and without trading are as follows:\textsuperscript{23}

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

This yields the following conclusion:
Proposition 5. In a stochastic world, for the given efficient effort levels by both harvesters, the relative magnitudes of the probabilities of violation under individual quotas with and without trading depend on $\bar{h}$. When $\bar{h}$ is low ($0 < \bar{h} < 0.5e^*$), the probability of violation under ITQs is greater than that under non-tradable quotas. Conversely, when $\bar{h}$ is high ($0.5e^* < \bar{h} < e^*$), the probability of violation under non-tradable quotas is greater than that under ITQs.

We can use Figure 2 to explain the basic intuition underlying Proposition 5. The red curve in Figure 2 is the cdf of the summation of the two uniform distributions, denoted $F_1(x)$. The black solid straight line denotes the cdf of one uniform distribution, denoted $F_2(x)$. The blue dotted straight line is a pseudo-cdf line, which doubles each horizontal ordinate of the cdf of one uniform distribution while keeping its corresponding vertical ordinate unchanged, denoted as $F_3(x)$. For $0 \leq \bar{h} < 0.5e^*$, i.e., $0 \leq 2\bar{h} < e^*$ (e.g., $\bar{h}_1$ in the graph), we have $\Pr(h_1^* > \bar{h}) = |AB| < EF = \Pr(h_1^* + h_2^* > 2\bar{h})$, 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 $\Pr(h_1^* > \bar{h}) = |CD| > GH = \Pr(h_1^* + h_2^* > 2\bar{h})$. At $\bar{h} = 0.5e^*$, i.e., $2\bar{h} = e^*$, $\Pr(h_1^* > \bar{h}) = \Pr(h_1^* + h_2^* > 2\bar{h})$.

Proposition 5 implies that there is not a general ranking of the probabilities of violation under these two individual quota scenarios. The ranking depends on the magnitude of the quotas, as well as the nature of the underlying distribution of harvests. Here, for example, given that the individual harvest is assumed to be 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 violation under these two cases in different ranges. Thus, in general, i.e. for a general distribution, the ranking of the two probabilities is ambiguous.

4.1.2 Expected magnitudes of violation

Given the efficient effort levels, denote the expected unconditional magnitude of violation (hereafter, expected magnitude of violation for short) by $M^N = E[(h_1^* - \bar{h})|h_1^* > \bar{h}] \times \Pr(h_1^* > \bar{h})$ and $M^T = E[(h_1^* - \bar{h})|h_1^* + h_2^* > 2\bar{h}] \times P(h_1^* + h_2^* > 2\bar{h})$, respectively. Comparing $M^N$ and $M^T$ gives the following result:

16
**Proposition 6.** In a stochastic world, given the efficient effort levels by both harvesters, ITQs always have a smaller expected magnitude of violation for each harvester than non-tradable quotas, i.e., $M_T^f < M_N^f$.

Although the ranking of the probabilities of violation under these two individual quota scenarios is ambiguous, Proposition 6 shows that the ranking of their expected magnitude of violation is unambiguous. This is mainly because ITQs always have a lower expected conditional magnitude of violation than non-tradable quotas, i.e., $E[(h_i^* - \bar{h}) | h_i^* + h_j^* > 2\bar{h}] < E[(h_i^* - \bar{h}) | h_i^* > \bar{h}]$. Specifically, under non-tradable quotas, an individual harvester will face an additional quota charge if $h_i^* \in (\bar{h}, e^*)$. In contrast, under ITQs, he will face an additional charge if $h_i^* \in (2\bar{h} - h_{-i}^*, e^*)$, where $h_{-i}^*$ is the harvest amount of the other harvester. Therefore, ITQs have a lower expected conditional magnitude of violation. Furthermore, the impact of the expected conditional magnitude of violation on the expected (unconditional) magnitude of violation dominates the impact of the probability of violation, which makes the expected (unconditional) magnitude of violation always lower under ITQs.

**4.1.3 Optimal quota prices**

Although the ranking of the expected magnitudes of violation is unambiguous under these two individual quota scenarios, the relative magnitude of their optimal quota prices is ambiguous:

**Proposition 7.** In a stochastic world, the ranking of optimal quota prices under non-tradable quotas and ITQs depends on the quota $\bar{h}$. More specifically,

\[
\begin{align*}
&d < k_f^* < k_N^*, \quad \text{if} \quad 0 < \bar{h} < (\sqrt{129} - 7)e^*/8, \\
&d < k_N^* < k_f^*, \quad \text{if} \quad (\sqrt{129} - 7)e^*/8 < \bar{h} < e^*.
\end{align*}
\]

Figure 1 illustrates the case where $0 < \bar{h} < (\sqrt{129} - 7)e^*/8$, under which $k_f^* < k_N^*$. Intuitively, because private marginal benefits are the same across these two cases, i.e., $MB(e_i) = 0.5 - 2e_i$, optimal quota prices should be adjusted to reflect the differences in the marginal effect of effort on the expected magnitude of violation (i.e., $\partial M^f / \partial e_i, J = N, T$) so that the marginal effect of effort
on the expected charge, $\text{MEP}(e_i) = k^* \cdot (\partial M^J / \partial e_i)$, is equal under both scenarios (so that both scenarios induce efficient choices). When $\tilde{h}$ is low, $(\partial M^T / \partial e_i) > (\partial M^N / \partial e_i)$, and hence harvesters have less incentive to increase effort under ITQs than under non-tradable quotas, for any given $k$. Thus, in order to induce efficient effort, non-tradable quotas require a higher optimal quota price. Conversely, when $\tilde{h}$ is high, $(\partial M^T / \partial e_i) < (\partial M^N / \partial e_i)$, and hence harvesters under ITQs have more incentive to increase effort, for any given $k$. Therefore, in order to induce efficient effort, ITQs require a higher optimal quota price when $\tilde{h}$ is high.

4.1.3 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 charges and hence expected net profits. Combining results from subsections 4.1.2 and 4.1.3 yields the following conclusions on how the two policy scenarios affect expected charges and hence expected net profits:

**Proposition 8.** In a stochastic world, for optimally designed policies, ITQs yield a lower expected charge than non-tradable quotas, i.e., $E[T_{C_i}^T] < E[\Phi_i^N]$. This implies $E[\pi_i^T] > E[\pi_i^N]$.

Thus, since both policy scenarios yield efficient effort, regulators who seek to both induce efficient effort and reduce the negative impact of harvest restrictions on harvesters should prefer ITQs over non-tradable quotas.

4.2 Collective quotas: centralized collectives vs. decentralized collectives

4.2.1 Optimal quota prices

The main difference between these two scenarios is that decentralized collectives generate moral hazard. A centralized collective operates as if there is a single owner who sets the effort levels for all the vessels to maximize profit 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 decentralized collective, each harvester wants to maximize his own profit. Since each harvester will reap the full benefit from additional harvest that exceeds the group quota while only paying a fraction of the associated charge, each faces an incentive to undertake more effort than
is optimal for the group as a whole, which creates a moral hazard problem. As expected, decentralized collectives require a higher optimal quota price than centralized collectives to correct the moral hazard problem:

**Proposition 9.** When the outcomes are stochastic, for given quota $\overline{h}$, the optimal $k^*$ under the decentralized collectives is twice as large as that under centralized collectives, i.e., $k_D^* = 2k_C^*$.

As shown in Figure 1, harvesters under decentralized collectives have more incentive to increase effort than centralized collectives, for any given $k$. 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 decentralized collectives.25

4.2.2 Expected net profits

The probabilities of violation are the same under these two policy scenarios. The expected magnitudes of violation are also the same. Therefore, $E[\Phi_r^D] = 2E[\Phi_r^C]$, given $k_D^* = 2k_C^*$. We can summarize the results as follows:

**Proposition 10.** In a stochastic world, given the optimally designed policies, the aggregate expected total charge under the decentralized collectives is twice the aggregate expected total charge under the centralized collectives, i.e., $E[\Phi_r^D] = 2E[\Phi_r^C]$. Thus, centralized collectives yield a higher industry-level expected net profit than decentralized collectives.

In contrast to the typical effect of moral hazard, here moral hazard under decentralized collectives does not affect social welfare, given the optimally designed policies. Nevertheless, it does hurt harvesters by requiring a higher optimal quota price and hence increasing the total expected charge.

4.3 Individual quotas vs. collective quotas: ITQs vs. centralized collectives

The above two sections show that ITQs outperform non-tradable quotas and centralized collectives outperform decentralized collectives in terms of negative impacts on harvesters, given that both yield efficiency. Therefore, we will compare ITQs vs. centralized collectives in this section.

The probabilities of violation are the same under these two policy scenarios. The aggregate expected magnitudes of violation are also the same,
i.e., \(2 \times E[(h_i^* - \bar{h}) | h_i^* + h_z^* > 2\bar{h}] \times P(h_i^* + h_z^* > 2\bar{h}) = E[(h_i^* + h_z^* - 2\bar{h}) | h_i^* + h_z^* > 2\bar{h}] \times \Pr(h_i^* + h_z^* > 2\bar{h})\). However, they differ in the optimal quota prices, and hence the expected net profits.

4.3.1 Optimal quota prices

As we know, for any effort level, under certainty, the marginal effects of effort on the magnitude of violation are the same, i.e., \(\frac{\partial (h_i + h_z - 2\bar{h})}{\partial e_i} = \frac{\partial (h_i - \bar{h})}{\partial e_i}\). Nevertheless, when the outcomes are stochastic,

\[
\frac{\partial E[(h_i + h_z - 2\bar{h}) | h_i + h_z > 2\bar{h}]}{\partial e_i} = \frac{\partial E[(h_i - \bar{h}) | h_i + h_z > 2\bar{h}]}{\partial e_i} + \frac{\partial E[(h_z - \bar{h}) | h_i + h_z > 2\bar{h}]}{\partial e_i},
\]

which implies

\[
\frac{\partial E[(h_i + h_z - 2\bar{h}) | h_i + h_z > 2\bar{h}]}{\partial e_i} < \frac{\partial E[(h_i - \bar{h}) | h_i + h_z > 2\bar{h}]}{\partial e_i},
\]

because \(\frac{\partial E[(h_z - \bar{h}) | h_i + h_z > 2\bar{h}]}{\partial e_i}\) is negative. Intuitively, this is because, when \(e_i\) increases and hence \(h_i\) increases, the range for \(h_z\) satisfying the condition \((h_i + h_z > 2\bar{h})\), i.e., \((h_z > 2\bar{h} - h_i)\), expands leftwards on the axis. This inequality holds for any effort under uncertainty. If we denote \(M^c = E[(h_i + h_z - 2\bar{h}) | h_i + h_z > 2\bar{h}]\), equation (23) implies that \((\partial M^c / \partial e_i) < (\partial M^T / \partial e_i)\) for any \(\bar{h}\).

As a result, harvesters have more incentive to increase effort under centralized collectives than under ITQs, for any given \(k\), as shown in Figure 1. Again, optimal quota prices should be adjusted to reflect the differences in the marginal effect of effort on the expected magnitude of violation, which gives the following conclusion:

**Proposition 11.** In a stochastic world, to induce the efficient effort, centralized collectives require a higher optimal quota price than ITQs, i.e., \(k^*_c > k^*_T\).

4.3.2 Expected net profits

As discussed above, the total expected magnitudes of violation is the same under these two policy scenarios. The difference in the optimal quota prices leads to different expected charges, and hence different expected net profits:
Proposition 12. In a stochastic world, for optimally designed policies, ITQs yield a lower expected charge than centralized collectives, i.e., $E[TC_i^T] < E[\Phi_i^C]$. This implies $E[\pi_i^T] > E[\pi_i^C]$.

Although both ITQs and centralized collectives provide mechanisms for risk spreading, centralized collectives hurt harvesters by requiring a higher optimal price for additional quotas and hence increasing the total expected charge. As a result, ITQs yield higher industry-wide expected net profit than centralized collectives. Under uncertainty, both individual and collective quotas are equally efficient. However, when tradable, individual limits can lead to higher expected profit than collective limits. Because ITQs yield the highest industry-level expected net profits among these four optimally designed policies, regulators who seek for both efficiency and lower costs for harvesters should prefer ITQs to the other three alternatives.

5. Extension

The above discussion is based on the assumption that the two harvesters are identical. In this section, we will discuss which conclusions still hold and/or how results change when this assumption is relaxed.

As noted above, when $\vec{h} = 0$, i.e., in the absence of quota, the four policy scenarios reduce to a standard Pigouvian tax. Similar to the results with identical harvesters, setting $k_N^* = k_T^* = k_C^* = d$ and $k_D^* = 2d$ can induce the efficient effort even when harvesters are not identical. This is also consistent with the rule under a Pigouvian tax when there exists heterogeneity. Specifically, if the marginal damage ($MD$) is the same across firms (as under a linear damage function), the regulator can induce efficiency by setting the marginal tax rate equal to the marginal damage, i.e.,

$$i_N^* = i_T^* = 0.5i_D^* = i_C^* = MD = d \text{ (Baumol and Oates, 1988), and the distributional impact is the same as that with homogeneous harvesters. Specifically, the ranking of the expected charge per harvester is}$$

$$E[\Phi_i^N] = E[TC_i^N] = E[\Phi_i^C] = 0.5E[\Phi_i^D], \text{ and hence the ranking of the expected net profit per harvester is}$$

$$E[\pi_i^N] = E[\pi_i^T] = E[\pi_i^C] > E[\pi_i^D].$$

In the presence of harvest restrictions, i.e., $\vec{h} > 0$, under non-tradable quotas, the regulator can induce the efficient effort either by allocating the same amount of quotas to each harvester and charging different optimal prices for additional quota across individuals, or by charging the same quota price but assigning different limits across individuals. However, under ITQs the regulator cannot ensure efficiency through a mechanism with the same initial allocation but different optimal
quota prices, because he can only predict the range of the equilibrium trading price and not a unique price. However, the regulator can charge the same quota price across individuals and optimally design the initial allocation to reach the first best outcome.\textsuperscript{26}

Under a collective, the group faces a charge once the collective quota is violated, but no rewards if the harvest is below the aggregate limit, which makes the expected charges non-linear in effort levels. Therefore, under a centralized collective, to maximize total profits, a group with heterogeneous harvesters does not necessarily equate the marginal benefit of each harvester’s effort to the marginal social damage. In other words, by setting a single quota price for the centralized collective as a whole, the regulators cannot always reach the first-best outcome. Nevertheless, under a decentralized collective, the regulators can design a charge allocation rule, i.e., an optimal quota price for additional quota (i.e., charge rate) combined with a charge sharing ratio across members in the group, to induce the efficient effort levels.

Next we compare the distributional impact of these alternative policy scenarios. Because it is impossible to derive a closed-form solution for the second best under centralized collectives without strong assumptions, we only compare the industry-wide profits under non-tradable quotas, ITQs and decentralized collectives, given that these three scenarios yield the first best and the centralized collective does not. To be comparable, we assume the aggregate quota (equal to $2\bar{h}$) is the same under these three cases. Firstly, under non-tradable quotas, we focus on the alternative under which the regulator allocates the same quota but assigns different optimal quota prices to the two harvesters.\textsuperscript{27} We can derive the pair of optimal quota prices ($\bar{k}_{1}^*, \bar{k}_{2}^*$) as a function of $\bar{h}$ and hence the total expected net profit. Secondly, as mentioned above, under ITQs it is only possible to induce efficiency by allocating different quota amounts to the two harvesters and then setting the same quota price. We solve for ($\bar{h}_{1}^*, \bar{h}_{2}^*$) as a function of any given quota price, then solve for the optimal quota price such that $\bar{h}_{1}^* + \bar{h}_{2}^* = 2\bar{h}$. This further allows us to obtain the values of ($\bar{h}_{1}^*, \bar{h}_{2}^*$) and hence the aggregate expected net profit. Finally, under decentralized collectives, we can solve for the overall optimal quota price with a charge sharing ratio among its members and then calculate the total net profit. Although it is difficult to directly compare these scenarios under general parameter values, when $d = 0.7$ and $C_{2}(e) = 0.5e_{2}^{2}$, we find that ITQs yield a higher aggregate expected net profit than non-tradable quotas, whereas non-tradable quotas yield a higher total expected net profit than decentralized collectives.
6. Conclusion

In the past few decades, innovations in fisheries management have focused on designing different mechanisms to allocate property rights. Often, property rights are created through a limit on the harvest of a target species or bycatch imposed by regulators or fishery managers. A key question is whether to assign harvest rights to individuals or collectives. Both collective quotas and individual tradable quotas provide a mechanism for risk sharing under uncertainty. However, collective quotas have the problem of moral hazard when decisions are made in a decentralized way. The purpose of this paper is to evaluate the efficiency of collective quotas vs. individual quotas when both moral hazard and uncertainty are important. We base our analysis on a theoretical model that allows us to answer the question of how moral hazard and risk pooling interact to affect the efficiency of collective quotas, a question that has not been studied in the previous theoretical literature. The model allows us to examine whether a collective quota can lead to a more efficient outcome than individual quotas when faced with these two features if harvesters can purchase additional quota when they exceed allocated quota limits due to random variation in harvests.

Specifically, we evaluate the efficiency of collective quotas vs individual quotas by comparing four alternative policy scenarios: (1) non-tradable quotas, (2) ITQs, (3) decentralized collectives, and (4) centralized collectives. We find that all four alternatives can reach the first best outcome, when optimally designed. Therefore, there is no efficiency basis for preferring one policy scenario over the others. However, correcting the different incentives underlying the four scenarios results in different individual and industry-level expected net profits across these scenarios. Thus, although the efficiency impacts are the same, the four alternative policy scenarios differ in their distributional impacts.

Given optimally designed policies, we find that the risk spreading mechanism of ITQs makes harvesters better off under ITQs than under non-tradable quotas. Furthermore, because of the moral hazard problem, decentralized collectives require a higher optimal quota price and hence yield a lower industry-level expected net profit than centralized collectives. Finally, although both ITQs and centralized collectives provide an opportunity for risk sharing, centralized collectives hurt harvesters in terms of distributional impact by requiring a higher optimal price for additional quota. As a result, ITQs yield higher aggregate expected profit than centralized collectives. In other words, under uncertainty, both individual and collective quotas can lead to efficiency, but, when tradable, individual limits impose lower costs on harvesters than collective limits.

Annala, John H. 1996. New Zealand's ITQ system: have the first eight years been a success or a failure?. *Reviews in Fish Biology and Fisheries* 6, no. 1: 43-62.


### Table 1
Examples under four policy scenarios

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<th>Policy scenarios</th>
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<td>Individual limits without trading</td>
<td>orange roughy fishery in Namibia</td>
<td>Costello (2012)</td>
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<td>(&quot;Non-tradable quotas&quot;)</td>
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<td>herring fishery in Iceland</td>
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<td></td>
<td>South Atlantic wreckfish fisheries in the U.S.</td>
<td>Criddle and Macinko (2000)</td>
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<td>North Pacific halibut and sablefish fisheries in the U.S.</td>
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<td>where effort choices are decentralized</td>
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<td>where effort choices are made collectively</td>
<td>deep-sea crab fishery (<em>Crabco</em>) in New Zealand</td>
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<td>(&quot;centralized collectives&quot;)</td>
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Figure 1

Comparison of the optimal $k^*$ under four policy scenarios

Note: This graph shows the case where $(\sqrt{129} + 7)h / 10 < e < 8h / 3$ (or equivalently, $3e / 8 < h < (\sqrt{129} - 7)e / 8$), which implies $k_r^* < k_n^* < k_c^* < k_d^*$. 

\[ * \]
Figure 2
Comparison of probabilities of violation

Notes:
If $0 < \bar{h} < 0.5 e^*$ (e.g., $\bar{h}_1$ in the graph), then $\Pr(h_1 > \bar{h}) = |AB| \leq |EF| = \Pr(h_1 + h_2 > 2\bar{h})$.
If $0.5 e^* < \bar{h} < e^*$ (e.g., $\bar{h}_2$ in the graph), then $\Pr(h_1 > \bar{h}) = |CD| \geq |GH| = \Pr(h_1 + h_2 > 2\bar{h})$. 
Bonzon et al. (2013) also discuss community fishing quotas, which are allocated to a community as a whole.

Alternatively, a group of individuals might hold the right to manage a common property resource without any externally-imposed constraints on resource use. A large literature exists on the extent to which groups can efficiently manage such resources without any government intervention. See, for example, Baland and Platteau (1997, 2003), Bavinck (1996), Dayton-Johnson (2000), Oakerson (1986), and Ostrom (1990).

For example, ITQs have been shown to increase efficiency in fisheries (Arnason 1990; Grafton et al., 2000). However, they can also lead to an inefficient spatial or intra-seasonal distribution of harvest activities (Boyce, 1992; Clark, 1980; Costello and Deacon, 2007; Holland, 2004; Wilen et al., 2012) and do not eliminate competition impacting ex-vessel prices (Fell, 2010).

In this paper, we use the term “moral hazard” to describe the outcome where individuals making private decisions fail to consider the direct impact of those decisions on others and hence tend to over-exploit a resource or under-provide effort. This is broader than the concept of moral hazard in standard principal-agent models, which hinges on uncertainty and the unobservability of effort. Here, for example, moral hazard would arise under collective limits with individual decisions (decentralized collectives) even if there were no uncertainty.

In practice, 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). Our interest here is in the coordination of effort levels. However, even when effort choices are made non-cooperatively, members of the group might still make other decisions collectively. For example, they might collectively assign who can fish where on a given day, even if they do not dictate how much an individual can fish in the assigned location (Gaspart and Seki, 2003; Platteau and Seki, 2001).

This is in addition to the primary, well-known argument made in support of allowing permits or quotas to be traded, namely, that trading will increase efficiency when firms have heterogeneous costs (Farrow et al., 2005; Montgomery, 1972; Muller and Mendelsohn, 2009; Tietenberg, 1985). This benefit exists even when all outcomes are deterministic.

Bonzon et al. (2013) argue that an individual limit is preferable if a fishery manager aims to encourage flexibility and economic efficiency, while a group limit is preferable if the members in the group have strong social bounds or common interests and values and the group can collectively monitor and manage the fishery at a low cost. However, they do not provide a theoretical model to support these conclusions.

Holland and Jannot (2012) empirically identify the importance of both moral hazard and risk pooling when sharing quota.

Since harvesters in general have no incentive to trade quotas under collective limits, we do not consider quota markets for the cases that involve collective limits.

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 have focused on fairness, such as the distribution of rents (Cancino et al., 2007).

The spatial and temporal arrangement of fishing effort has been studied in, for example, Cancino et al. (2008), Deacon et al. (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).

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.

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

As mentioned in the introduction, this type of external damages has also been noted by Arnason (2012), Holland (2004), Holland and Schnier (2006) and Wilen et al. (2012).

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).

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.

We focus on the static (single season) case. For the dynamic cases, \( \bar{n} \) could be adjusted to reflect fish stock assessments, while \( k \) will be used to induce the efficient effort.
Note that this first order condition only holds for the interior solution. It is not an exclusive description of the optimal solutions. This is also true for the first order conditions below. We are interested in the case where the constraints are binding (i.e., interior solutions).

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.

More precisely, \( E[TC] = P(h_1 + h_2 > 2\bar{h}) \cdot E[TC \mid h_1 + h_2 > 2\bar{h}] + P(h_1 + h_2 = 2\bar{h}) \cdot E[TC \mid h_1 + h_2 = 2\bar{h}] + P(h_1 + h_2 < 2\bar{h}) \cdot E[TC \mid h_1 + h_2 < 2\bar{h}] \). Furthermore, \( P(h_1 + h_2 = 2\bar{h}) = 0 \), because the probability function is continuous, and \( E[TC \mid h_1 + h_2 < 2\bar{h}] = 0 \). Therefore, the total expected costs can be simplified as \( E[TC] = P(h_1 + h_2 > 2\bar{h}) \cdot E[TC \mid h_1 + h_2 > 2\bar{h}] \).

Note that when faced with a group charge, harvesters in both cases have no incentive to trade quota either ex ante or ex post, because they are not being charged for violating individual limits, implying that the marginal benefit of purchasing an additional unit of quota from the other harvester 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 policy scenarios with collective limits.

Furthermore, the \( k^* \)'s are increasing in \( \bar{h} \) and \( \bar{k}^* \)'s \( \to \infty \) when \( \bar{h} \to \bar{e} \).

Note that these rankings, Result 1 and the discussion of Figure 1 also hold for general symmetric effort level \( e \), and can be further extended to cases with asymmetric effort levels.

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 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 Proposition 5.

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 water quality.

This is in contrast to the standard result for permit trading, where the initial allocation of permits has no efficiency effects. This is because in our model, harvesters will be charged if the limits are exceeded, but not be rewarded if the harvest falls below the quotas, and hence the marginal effect of effort on expected charge is a non-linear function of effort.

Alternatively, we can consider the policy of allocating different quota but assigning the same quota prices to two harvesters. The conclusions here still hold.