Regulating a common-pool resource when extraction costs are heterogeneous: fees versus quotas

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Abstract

We examine the choice of instrument to regulate a common pool resource, a fishery, previously extracted under free access. The fishermen have heterogeneous extraction costs. The goal of the regulation is to reduce the total extraction effort. It must be accepted by fishermen: they all must be better-off with the regulation than under free-access. We compare the efficiency of two regulatory instruments: a fee/subsidy scheme (an access fee for the fishery and a subsidy for those who stop fishing) and uniform (and non-transferable) quotas. In this set-up, the first best management of the resource requires to exclude the less efficient fishermen. It might be achieved with the fee scheme but not with uniform quota. However, due to the acceptability constraints, a quota might lead to a higher reduction in fishing effort.

Key Words: common pool resource; heterogeneous extraction cost; fee; quota.

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1 Introduction

Worldwide, many natural resources such as fisheries are still exploited under free-access. Since Gordon (1954) at least, it is well-known that the free-access extraction of a common-pool resource leads to over-exploitation. To avoid the resource exhaustion and to improve its management, the fishing industry has been highly regulated lately through various instruments such as norms, quotas, fees and subsidies. These regulatory instruments have heterogenous impacts of fishermen, depending on their technology and opportunity costs. Some might gain or loose more than others with the same regulation. The design of fishery regulation should certainly take into account its impact on the fishermen's incentives and welfare.

The aim of this paper is to examine two sets of fishery regulatory instruments when fishermen differ by their opportunity cost of fishing. The first one is a market-based regulation. It asks fishermen to pay access fees and subsidies those who exit the fishing industry (e.g. by buying out their vessel). The second one imposes a non-transferable quota. Both instruments are commonly used worldwide (Hannesson, 2004; Bjorndal, 1998; Hartwick, 1998). Importantly, the two instruments must be sustainable (e.g that the subsides must be enterally financed by the access fees). It must also be accepted by all fishermen in the sense that they must be better-off under the regulation regime than under free-access extraction.

The goal of the regulation is to reduce the fishing activity. Under the assumption of heterogenous and constant fishing opportunity cost, the efficient way to reduce fishing is to exclude the less efficient fishermen (to keep only the more efficient ones). This can be done with an access fee on the fishery that finances a subsidy for leaving the fishing industry. But the efficiency of this fee/subsidy regulation might be constraint by the sustainability or the acceptability condition. As a consequence, the first-best fishery exploitation might not be achieved because (i) either it requires to subsidy more than the amount collected with fees, or (ii) some fishermen loose compared to the free-access and, therefore, will veto the regulation. The acceptability condition might be more easily fulfilled with a uniform quota. Indeed, a uniform quota might reduce the fishing activity more than the fee/subsidy scheme, although without selecting the more efficient fishermen. Hence, to be unanimously accepted, the choice of the regulation instrument trades-off between selecting efficient fishermen (with the fee/subsidy scheme) and reducing more extraction (with the quota).

The paper builds on Gordon (1954)'s static model of fisheries. It introduces heterogeneous costs into the seminal model which yields different results. Indeed, under free access, homogeneous fishermen will enter so long as rent is positive. At the equilibrium, every fishermen obtain a nil rent. Furthermore, the marginal cost of the fishing effort is equal to its marginal product. With heterogeneous fishermen, the marginal product is still equal to the marginal cost of fishing but of the fisherman with the highest cost. This less efficient fisherman obtains no rent but all other fishermen (with lower cost) obtain a positive rent. Yet free access leads to over-exploitation and, therefore, call for regulation. We argue here that the choice of the regulatory instrument to reduce fishing is not obvious with heterogenous costs. It is therefore worth to be pursued.

Androkovich and Stollery (1991) compared tax and quota to regulate a fishery in a demand uncertainty but homogeneous fishermen context. Their results advise a tax implementation, although the welfare losses arising from quota are minor. Because of political difficulty of imposing a tax, quota should be a preferred regulatory instrument. We also compared those instruments without any demand uncertainty but with heterogeneity.

Jensen and Vestergaard (2001) showed that taxes are preferred over Individual Transferable Quotas (ITQs) if prices are constant and the marginal cost function has a positive slope. They also remark that ITQs seem to be easier to implement because fishermen collect directly the rent which is opposed to taxes collected by society. Baland and Francois (2004) compared the impact of insurance on a common property resource and on private property. Their results exposed that privatization seems to be harmful for agents with low external opportunity cost when markets are incomplete; which is currently the case in LDCs. And common property resources had better property insurance when agents are risk averse.

Johnson and Libecap (1982) examine problems of overcapitalization and excessive labor input use in fisheries. They focus their study particularly on Texas shrimp industry, where regulations are incomplete because of heterogeneity on fishermen. Because of uncertainty of biological knowledge of fish stock, and heterogeneity on terms of effort and catch, enforcement regulation is costly. The private contracting is a better instrument such that all margin of dissipation will be regulated and lead to consensus. We analyze here the impact of regulation instruments on heterogeneous fishermen exploiting the same stock of resource, such that fishing restriction respect everybody incentives, and make project still attractive, in a way to decrease the excessive amount of input use.

Ambec and Hotte (forthcoming) consider a community composed of agents who differ from their opportunity cost of extraction as assumed here. However, they focus on privatization as the sole regulatory instrument, whereas here we focus on quotas and fees.

The paper is organized as follow. Section 2 presents the model, describes the optimal extraction rate and free access extraction rate. Section 3 and 4 expose the regulations system (fee/subsidy and quota) and regulation's impact on the fishery activity. Section 5 compares the two regulatory instruments. Section 6 provides concluding remarks.

2 The model

Consider a community of individuals extracting a common-pool natural resource. Members of the community differ solely by their opportunity cost c which represents the (constant) marginal cost of one unit of extraction effort x. Those (marginal) costs within $[\underline{c}, \bar{c}]$ are distributed according to some distribution $G(c)$ and density $g(c)$. c is private information (non observable by the regulator). Individual are endowed with same extraction capacity $\bar{x}$.

Even though opportunity costs are heterogeneous, individuals share the benefit of extraction (per unit of extraction effort). Each individual obtains the average product of extraction $\phi(X)$, where X represents the total extraction effort of the community. Typical examples of such common-pool natural resources include fisheries, forests for wood or fuel-wood, hunting grounds and pastures. For easy exposition, the common-pool resource will be called the "fishery" and the extractors the "fishermen".

The total harvest is denoted $h(X)$. Therefore, the average product of effort is simply $\phi(X) = h(X)/X$. The price of the resource is normalized to 1.

In this economy, an (effort) allocation is a set of individual (extraction) efforts $\{x(c)\}_{c\in[\underline{c},\bar{c}]}$ (hereafter denoted $\{x(c)\}$), where $x(c)$ stands for individual c's effort. It is a mapping from $[\underline{c}, \bar{c}]$ to $\mathbf{R}_+$. It yields an aggregate effort level:

$$X = \int_{\underline{c}}^{\bar{c}} x(c)dG(c). \tag{1}$$

The profit of a fisherman c with allocation $\{x(c)\}$ is thus $x(c)[\phi(X) - c]$. The total welfare W is just the sum of the profits,

$$W(\{x(c)\}) = \int_{\underline{c}}^{\bar{c}} x(c)[\phi(X) - c]dG(c).$$

We first characterize two benchmark allocations: the first-best one and the one implemented under a free-access of the fishery.

2.1 The first-best extraction

The first best effort allocation $\{x^*(c)\}$ maximizes the total benefit of fishing W subject to the capacity constraints $x(c) \leq \bar{x}$. The program can be simplified with the straightforward observation that each fishermen use either all their effort capacity or do not fish at all.

Lemma 1 *At the first-best, there exists a threshold c^* such that fishermen with $c < c^*$ fish up to their capacity whereas those with $c > c^*$ do not fish at all.*

Proof relegated in Appendix.

Since marginal cost are constant, then, with excess capacity, it is efficient to use the full capacity of the lower cost fishermen and exclude the high cost fishermen. The total fishing effort is thus:

$$X^* = \int_{\underline{c}}^{c^*} \bar{x} dG(c) = \bar{x}G(c^*). \tag{2}$$

Thanks to Lemma 1, we only need to identify the threshold cost c^* to fully characterize the first-best allocation. It solves the following program:

$$\max_c \int_{\underline{c}}^{c} \bar{x}[\phi(\bar{x}G(c)) - c)dG(c).$$

The first-order condition yields:

$$\bar{x}[\phi(X^*) - c^*] = -\phi'(X^*)\bar{x}^2 G(c^*).$$

It tells us that the marginal benefit of increasing the threshold cost should be equal to its marginal cost. The marginal benefit is an increase of benefit net of fishing cost (the left-hand side) whereas the marginal cost is a reduction of the average product (the right-hand side). It leads to $c^* = X^*\phi'(X^*) + \phi(X^*)$ where X^* is defined by (2). Since, by definition, $X\phi'(X) + \phi(X) = h'(X)$, then:

$$c^* = h'(X^*). \tag{3}$$

At the first-best, the threshold extraction cost should be equal to the marginal revenue. Fishermen $c < c^*$ use their effort capacity, i.e. $x^*(c) = \bar{x}$ for every $c < c^*$. Those with $c > c^*$ do not fish, i.e. $x^*(c) = 0$.[1]

We now turn to free access extraction.

2.2 The free-access extraction

Consider now the resource extraction is in a free access regime, hereafter denoted by FA. Allocation implemented under a free access of the fishery is denoted by $\{x^{FA}(c)\}$. The program can be simplified as remarked in the first best allocation, each fishermen use either all their effort capacity either do not fish at all.

[1]Notice, with a continuum of fishermen type as assumed here, the fishermen with the threshold marginal cost c^* can either fish at any effort level or not at the first-best, it does not change significantly the total effort level X^*.

Lemma 2 *Under free access, there exists a threshold c^{FA} such that fishermen with $c < c^{FA}$ fish up to their capacity whereas those with $c > c^{FA}$ do not fish at all.*

Proof relegated in Appendix.

Fisherman will enter fishery until their rent his positive or null. Previous condition is bound, i.e. the latter fisher (c^{FA}) who can extract makes zero profit. The free access condition yields:

$$\phi(X^{FA}) = c^{FA}. \tag{4}$$

The total fishing effort under free access is thus:

$$X^{FA} = \int_{\underline{c}}^{c^{FA}} \bar{x} dG(c) = \bar{x}G(c^{FA}). \tag{5}$$

Under free access, the threshold extraction cost should be equal to the average revenue. Fishermen $c < c^{FA}$ use their effort capacity, i.e. $x^{FA}(c) = \bar{x}$ for every $c < c^{FA}$ and earn a positive rent from the fishery. Those with $c > c^{FA}$ do not fish, i.e. $x^{FA}(c) = 0$ for every $c > c^{FA}$. The critical individual, c^{FA}, is indifferent between extracting (using his effort capacity $x^{FA}(c) = \bar{x}$) or not the fishery ($x^{FA}(c) = 0$), in both cases his rent is null. We now compare the free access and efficient fishing efforts.

Proposition 1 *The total fishing effort obtained under the first best allocation is below the free-access total effort level*

$$X^* < X^{FA}. \tag{6}$$

Proof relegated in Appendix.

Figure 1: The first best and free access regimes.

The free access regime is inefficient because what tends to get equated among alternative uses is the average product (see point A on figure 1) instead of its marginal product (see point B on figure 1). The open access regime holds a large number of fisher, excessive amount of effort are used for a given harvest. Regulation instruments such as fees or quotas could reduce total effort of extraction and, therefore, improve efficiency. We examines successively two regulatory instruments: a fee and subsidy scheme, and a uniform quota.

3 Regulating with a fee and subsidy scheme

3.1 Presentation of the regulation program

We first consider a fix access fee τ and a fix subsidy s for those who accept not to fish anymore. Thus the planner collect the rent of fees and redistribute at maximum the fee revenue to losers (budget balanced constraint). The regulatory instrument must be accepted by all fishermen in the sense that they must be better off with the regulation than under free access (acceptability constraints). If not the planner will be press not to implement this fee, or if it is implemented, to compensate those who lose.

The introduction of a fee/subsidy scheme decreases access until a certain opportunity cost denoted c^τ. It corresponds to the last individual who can participate to fishery, and who is indifferent to participate or not to the fishery (incentive constraint).The total fishing effort obtained under regulation is:

$$X^\tau = \int_{\underline{c}}^{c^\tau} \bar{x} dG(c) = \bar{x} G(c^\tau). \quad (7)$$

Under fee/subsidy scheme we limit access until the threshold extraction cost c^τ.Community is now composed of three types of agents. First type corresponds to fishermen $c < c^\tau$ who participate to resource extraction and pay a fix fee $\tau < 0$. The critical individual, c^τ, is indifferent between extracting (and paying the fee) or not the fishery (and receiving the subsidy).Those with $c^\tau < c < c^{FA}$, the second type, do not any longer fish but receive in compensation a fix subsidy s. Last, individuals $c > c^{FA}$ are still excluded from fishery. Without loss of generality we can ignore this latter type.

In this set-up, regulatory implementation requires to be accepted by all fishermen (type 1 and 2), indifferent for fishermen with opportunity cost c^τ, and be budget balanced.

Figure 2: The regulatory regime.

Incentive constraint: The regulation should be such that fisherman c^τ (the last individual who fishes) is indifferent between exploiting fishery or paying a fee, and not exploiting by receiving a subsidy. The incentive constraint is represented on Figure 2 by point D.

$$\bar{x}[\phi(X^\tau) - c^\tau] + \tau = s. \quad (8)$$

The left hand side of (8) is the profit earned from fishing while the right hand side is the profit earned when agent stop fishing. Fishermen c^τ who still participate have to pay a fee and renounce to receive a subsidy s.

Acceptability constraints: In addition, every fishermen should be better off under regulation restriction than under free access, i.e. their gain earned with regulation should be superior or equal to their gain in the previous regime, it yields the following condition for every $c \leq c^\tau$: $\bar{x}[\phi(X^\tau)-c]+\tau \geq \bar{x}[\phi(X^{FA})-c]$. And a sufficient condition for every fishermen $c \leq c^\tau$:

$$\bar{x}[\phi(X^\tau)-c^\tau]+\tau \geq \bar{x}[\phi(X^{FA})-c^\tau]. \tag{9}$$

For every agents $c^\tau \leq c \leq c^{FA}$, acceptability constraint is $\bar{x}[\phi(X^{FA})-c] \leq s$, thus sufficient condition is:

$$\bar{x}[\phi(X^{FA})-c^\tau] \leq s. \tag{10}$$

Condition (9) says that, at the maximum, the amount of the fee should equates the difference between average product under regulation and free access regime (see Figure 2, for every c^τ (AD) is greater than (A'H)). An other way to illustrate the acceptability constraint is to remark that fishermen who do not exploit anymore fishery are better off with a subsidy, see equation (10). This constraint is on the Figure 2 represented by (for every $c^\tau \leq c \leq c^{FA}$ (DG) is greater than (HF)).

Budget balanced constraint: Finally, the total amount of subsidy should be lower or equal to total amount of fee collected (confer to Figure 2, area (ABCD) should be greater than (DEFG)) , in a sense, regulatory project should be viable.

$$-\tau \int_{\underline{c}}^{c^\tau} g(c) \geq \ s \int_{c^\tau}^{c^{FA}} g(c) \Leftrightarrow -\tau G(c^\tau) \geq s[G(c^{FA})-G(c^\tau)]. \tag{11}$$

We derived necessary conditions for the implementation of fishery management with an acceptable and budget balanced fee/subsidy scheme. Let now see if regulator could plan a fee/subsidy scheme such that aggregate effort is reduced until c^τ, and such that project is budget balanced and accepted by all fishermen. The regulation must satisfy conditions (8), (9), (10) and (11). This is equivalent to verify the following conditions:

$$\bar{x}[\phi(X^{FA})-\phi(X^\tau)] \leq \tau \leq \frac{\bar{x}[\phi(X^\tau)-c^\tau](G(c^\tau)-G(c^{FA})}{G(c^{FA}))} \tag{12}$$

$$\bar{x}[\phi(X^{FA})-c^\tau] \leq s \leq \frac{\bar{x}[\phi(X^\tau)-c^\tau]G(c^\tau)}{G(c^{FA})}. \tag{13}$$

A necessary condition to (12) and (13) to hold is:

$$\frac{\bar{x}[\phi(X^{FA})-c^\tau]}{\bar{x}[\phi(X^\tau)-c^\tau]} \leq \frac{\bar{x}G(c^\tau)}{\bar{x}G(c^{FA})}. \tag{14}$$

It yields the following proposition:

Proposition 2 *A fee/subsidy scheme reducing fishery access until the level* c^τ *is implementable if:*

$$\frac{\bar{x}[\phi(X^{FA}) - c^\tau]}{\bar{x}[\phi(X^\tau) - c^\tau]} \leq \frac{X^\tau}{X^{FA}}.$$

We defined a necessary condition to decrease aggregate fishing effort under the free access level ($c^\tau < c^{FA}$): if profit improvement of individual c^τ is lower or equal to the decrease in aggregate effort, then regulatory instrument is implementable. We examine in next subsection the maximization program, and we study under which conditions the regulation limits aggregate effort until the first best level ($c^\tau = c^*$), or a second best level ($c^\tau = c^{SB}$).

3.2 The maximization program

The regulator will choose the level of s and τ that maximize the total welfare under the incentive constraint (see equation 8), acceptability constraint (see equation 9 or 10) and budget balanced constraint (see equation 11). His problem can thus be expressed as follows:

$$\max_{s,\tau} \int_{\underline{c}}^{c^\tau} g(c)[\bar{x}(\phi(X^\tau) - c) + \tau]dc + \int_{c^\tau}^{c^{FA}} sg(c)dc$$

such that:

$$\begin{cases} \tau G(c^\tau) + s(G(c^{FA}) - G(c^\tau)) \leq 0 & (\lambda) \\ \bar{x}[\phi(X^{FA}) - c^\tau)] - s \leq 0 & (\beta). \end{cases}$$

The left-hand side of the maximization corresponds to the total surplus of fishermen who still exploit ($\underline{c} < c < c^\tau$), while the right-hand side corresponds to the total subsidies distributed to fishermen who stop fishing ($c^\tau < c < c^{FA}$). The other agent don't participate to resource extraction and receive none rent from fishery. Parameter λ corresponds to the multiplicator of the budget balanced constraint (see equation 11) , and parameter β is the multiplicator corresponding to the acceptability constraint (see equation 10).

Lemma 3 *The regulatory instrument limit access until* c^τ *such that:*
(i) $\beta = G(c^{FA})(\lambda - 1)$

(ii)$\lambda \geq 1$ *and* $\beta \geq 0$

(iii)$c^\tau = h'(X^\tau) + \beta\frac{G(c^{FA}) - G(c^\tau)}{g(c^\tau)(G(c^{FA}) + \beta)}$ *or* $c^\tau = h'(X^\tau) + (\lambda - 1)\frac{G(c^{FA}) - G(c^\tau)}{\lambda g(c^\tau)}$.

Proof relegated in Appendix.

The regulatory instrument can limit access until c^τ if and only if the parameter associated to the budget balanced constraint is strictly positive ($\lambda \geq 1 \Leftrightarrow \lambda > 0$); in that case the budget balanced constraint is bound. The multiplicator associated to the acceptability constraint can be positive or null (β). We could already remark that if parameter $\beta = 0$, then $c^\tau = c^*$. Depending on the value of the multiplicator associated to the acceptability constraint β, the regulator can reach the first best level or the second best level. The allocation implemented under second best regulation is identified by the threshold c^{SB}.

The total fishing effort obtained at second best is denoted by:

$$X^{SB} = \int_{\underline{c}}^{c^{SB}} \bar{x} dG(c) = \bar{x}G(c^{SB}). \tag{15}$$

The following proposition gives conditions on first best and second best level implementation.

Proposition 3 *(i) The aggregate effort level can be reduced until the first best allocation if and only if it fulfills the following necessary and sufficient conditions:*

$$\beta = 0 \quad \textit{and} \quad \frac{\bar{x}[\phi(X^{FA}) - c^*]}{\bar{x}[\phi(X^*) - c^*]} \leq \frac{X^*}{X^{FA}}.$$

Thus $c^\tau = c^* = h'(X^*)$, *and* (s, τ) *such that* $\begin{cases} \tau = \frac{\bar{x}[\phi(X^*) - c^*](G(c^*) - G(c^{FA})}{G(c^{FA}))} \\ s = \frac{\bar{x}[\phi(X^*) - c^*]G(c^*)}{G(c^{FA})}. \end{cases}$

(ii) If previous conditions are not satisfied, aggregate effort can be reduced until the second best level, it requires those conditions:

$$\beta > 0 \quad \textit{and} \quad \frac{\bar{x}[\phi(X^{FA}) - c^{SB}]}{\bar{x}[\phi(X^{SB}) - c^{SB}]} = \frac{X^{SB}}{X^{FA}}.$$

Thus $c^\tau = c^{SB} = h'(X^{SB}) + \beta \frac{G(c^{FA}) - G(c^\tau)}{g(c^\tau)(G(c^{FA}) + \beta)}$, *and* (s, τ) *such that* $\begin{cases} \tau = \bar{x}[\phi(X^{FA}) - \phi(X^{SB})] \\ s = \bar{x}[\phi(X^{FA}) - c^{SB}]. \end{cases}$

Proof relegated in Appendix.

The first best is implementable if the profit improvement of individual c^* is lower or equal to the decrease in aggregate effort. In that case, regulator have a budget balanced (makes zero profit) and could enforce the lowest fee implementable with the highest subsidy implementable. If the first best cannot be implementable, and if the profit improvement of individual c^{SB} is equal to the decrease in aggregate effort, regulator reduces access until the second best level, and enforces the highest fee with the lowest subsidy, with a budget balanced ($\lambda > 0$).

A fee/subsidy scheme permits to reduce access compared to the free access level. If regulatory instrument do not fulfill conditions to reach the optimal allocation, access is reduced until the second best level witch is superior to the one implemented at first best.

Proposition 4 *The total effort level that can be reached at second best level is below the one implemented in free access, and above the one implemented at first best:*

$$X^* < X^{SB} < X^{FA}.$$

Proof relegated in Appendix.

In this section, we have shown it is possible to implement a regulation system in order to limit access of resource either at the first best, either at second best, depending on the value of parameter β (see proposition 3). Under regulation system we diminish the total level of effort (see proposition 4). All fishermen must pay a fix fee if they want/can participate to the extraction, others receive a fix subsidy. We found conditions on the regulatory instrument implementation at the first and second best level: in both cases, if profit improvement of individual c^*, respectively c^{SB}, is lower or equal, respectively equal, to the decrease in aggregate effort, then regulatory instrument is implementable.

In the following section, we provide the implementation of a tax proportional on output or a tax proportional on input.

3.3 Fee proportional on input and on output

In the previous regulation system, the fee does not depend on the opportunity cost, it is fixed. We could imagine this is unequal; fishermen with low cost of extraction should pay a higher tax, because their rents are bigger than fishermen with high cost. We still suppose, for ease of exposition that the amount of subsidy should remain the same; it is still fixed, every agent receives the same subsidy when they stop fishing.

Fee on output: The program is in this case rewrite as follows; the rent of each fishermen characterized by $c < c^\tau$ is now equal to: $(1 + \gamma)\bar{x}\phi(X^\tau) - \bar{x}c$, with $\gamma < 0$ the output multiplier of fee. And individual such that $c^\tau < c < c^{FA}$receive a fix subsidy s. The rent is $c < c^\tau$.

Fee on input: In that case the objective is to limit the capacity of extraction, suppose that regulator impose a fee proportional on $\bar{x}$. Profit earned for every $c < c^\tau$ is: $\bar{x}(\phi(X^\tau) - c) + \theta\bar{x}$, with $\theta < 0$ the input fee multiplier.

Proposition 5 *The effort restriction X^τ can equivalently be achieved with a fee on output $\gamma = \frac{\tau}{\bar{x}\phi(X^\tau)}$, or can equivalently be achieved with a fee on input $\theta = \frac{\tau}{\bar{x}}$, instead of the fix fee τ .*

Proof relegated in Appendix.

We provide now necessary conditions for the acceptability of a uniform quota.

4 Regulating with individual and uniform quotas

There exist different types of quota, we can limit the individual or total harvest (quota on output), the individual or aggregate effort (quota on input), or we can implement both at the same time. Those quotas could be individual and transferable.

In the case of quota on harvest, the government has several tools to enforce restriction. Authority can limit the catch of harvest (total allowable catch policy) if he finds that fish stock is threatened, to illustrate let's refer to the extreme case of quota on whales where it was prohibited to fish whales in certain regions (quota=0). Others restrictions on harvest may lead to an increase on aggregate effort, for instance if the catch is authorized only in a short period, fewer fishermen will be harvested with more effort, and they will race to catch as much as possible in this short time. There exist also gear and area restrictions. Individual quota could lead to efficient use level of effort; if each boat has a guarantee to harvest a certain amount of fish (total allowable catch) then fishermen will act as to minimize their cost on their total allowable catch. They won't have incentive to harvest as much as possible, they will concentrate on the quality of their catch, not on then quantity. Moreover if individual quotas are transferable it permits inefficient vessels to sell their quota than fish them if they think it will be more profitable.

In previous section we tried to reach a socially optimal equilibrium by implementing a fee/subsidy. Let's now see what's happen when we use uniform quota. In a first time we consider the case of quota on input, later we will study the case of quota on output. We will then compare this several regulation tool in order to capture the most efficient one.

4.1 Regulating with quota on input

Consider now that government implement a quota on input, i.e. there is restriction on the effort level of fishermen and not on the access, we keep the same number of fishermen as in open access but we reduce their capacity of extraction. This limitation on capacity could correspond to a gear or "season" restriction. The assumptions on the model derived in the first section still remain the same; we examine a simple case of quota without any transfer.

In the free access case we assumed that the capacity level was fixed at $\bar{x}$, government tries now to limit this capacity until $\widehat{x}$, with $\widehat{x} < \bar{x}$, quota is dedicated only to individuals who was authorized to fish under free access. Note in fact this quota concerned only fishermen characterized by $c < c^{FA}$, if we implement a quota without limiting access inefficient fishermen (i.e. fishermen with a cost of extraction higher than c^{FA}) will enter the resource due to the fact that their rent will be positive (see point B on the graphic). Indeed, a decrease in capacity induces an increase in average product. We thus do not authorize fishers above c^{FA} to participate (see point C on the graphic).

This quota system permits only to reduce the capacity of extraction. We won't be at the first best because we keep "inefficient" fishermen. There is no transferable quota, so we cannot exclude fishermen with a cost of extraction lower and closed to c^{FA}, we just avoid the entrance of worst fishers: $c > c^{FA}$.

As remarked in the first section, we assume that the capacity of extraction is binomial, i.e. $\exists c^{FA} \in [\underline{c}, \bar{c}]$ such that: $\forall c \leq c^{FA}$ then $x(c) = \widehat{x}$ and $\forall c \geq c^{FA}$ then $x(c) = 0$ (see Lemma 1). Total fishing effort is thus:

$$\widehat{X} = \int_{\underline{c}}^{c^{FA}} \widehat{x} dG(c) = \widehat{x} G(c^{FA}). \tag{16}$$

This quota induces an increase in the average product compared to the free access conditions (recall ϕ is a decreasing function):
$\widehat{x} < \bar{x} \Leftrightarrow \widehat{x} G(c^{FA}) < \bar{x} G(c^{FA}) \Leftrightarrow \phi(\widehat{X}) > \phi(X^{FA})$.
There is less extraction effort; it increases the net benefice per unit of effort. With uniform quota, it is easy to show that all fishermen will extract up to their quota. Indeed, in that case, the benefit of extraction per unit of unit $\phi(\widehat{X})$ exceeds its cost c for even $c \in [\underline{c}, c^{FA}]$ (because $c^{FA} = \phi(X^{FA}) < \phi(\widehat{X})$). The rent of each fishermen $c \leq c^{FA}$ is always positive and established as: $\widehat{x}(\phi(\widehat{X}) - c)$.

Figure 3: Regulating with quota on input.

What about the acceptability of this system: is every fishermen at least better off compared to free access regime? A priori this is not automatic.
Consider a fisherman with $c \in [\underline{c}, c^{FA}]$, the variation of his rent is ambiguous when the capacity of extraction decreases. Since $\phi(\widehat{X}) - c > \phi(X^{FA}) - c$ and $\widehat{x} < \bar{x}$, the sign of marginal benefit when quota reform is implemented is not clear: $\widehat{x}(\phi(\widehat{X}) - c) >, < or = \bar{x}(\phi(X^{FA}) - c)$.
The variation of his profit is equivalent to: $\widehat{x}\phi(\widehat{X}) - \bar{x}\phi(X^{FA}) + c(\bar{x} - \widehat{x})$.

The two first terms of the above equation correspond to the difference between product of harvest after and before the implementation of quota. The sign of this difference is, as we said before, ambiguous, if it is positive society improves its situation. The latter term is the variation of total cost, it is still positive; it is less costly to extract than in the free access. However fishermen with high cost, closed to c^{FA} for instance, benefit more than others. Indeed, the higher the extraction cost is, the higher the variation of profit will be.
We would like this profit variation to be positive: $c(\bar{x} - \widehat{x}) \geq \bar{x}\phi(X^{FA}) - \widehat{x}\phi(\widehat{X})$.

There exists a $\widetilde{c} \in [\underline{c}, c^{FA}]$ such that $\widetilde{c} = \frac{\bar{x}\phi(X^{FA}) - \widehat{x}\phi(\widehat{X})}{\bar{x} - \widehat{x}}$. For every $c < \widetilde{c}$ the variation of profit is negative, and for every $c > \widetilde{c}$ the variation of profit is positive.

Proposition 6 *A necessary and sufficient condition for quota on input to be acceptable is, for every $c < c^{FA}$:*

$$\underline{c} \geq \frac{\bar{x}(\phi(X^{FA}) - \widehat{x}\phi(\widehat{X}))}{\bar{x} - \widehat{x}} \Leftrightarrow \frac{\phi(X^{FA}) - \underline{c}}{\phi(\widehat{X}) - \underline{c}} \leq \frac{\widehat{X}}{X^{FA}}. \tag{17}$$

The decrease in aggregate effort should be higher or equal to the increase in profit for the more efficient fishermen with a quota compared to free access.

4.2 Regulating with quota on output

Imagine now regulator or government prefers to impose a quota on output, he wants to regulate the total harvest. We could think for instance he prefers quota on output than on input because it is easier to restrict aggregate harvest than effort.
The authorities want to introduce a quota; they impose a limitation on the harvest of every fishermen. This cut down the individual quantity of extraction uniformly, since fishermen face the same price; it is equivalent to limit revenue. Thus it decreases the total revenue. Due to the fact that the average of harvest is uniform and identical for every fishermen, implementing a quota remains the same as restricting the extraction $x(c)$.

Illustration: we limit the output of all fishermen, each should have a production such that $h(xG(c^{FA}) \leq \overline{h} \Leftrightarrow x \leq \frac{\overline{h}}{\phi(xG(c^{FA}))}$, where $\overline{h}$ is the individual fix objective restriction, remark that $\frac{\overline{h}}{\phi(xG(c^{FA}))}$ is the same for all fisher. Agent extracts since their rent is positive, they will fish at their maximal capacity, i.e. $x = \frac{\overline{h}}{\phi(xG(c^{FA}))}$ which is equivalent to a quota on input.

If we fix a quota on output as limiting the total harvest, it remains the same as fixing the capacity of extraction, in others words it is the same as imposing a quota on input. We

examined the implementation of two instruments, fee and quota, to regulate a common pool resource, previously extracted under free access.
Above these two instruments, which is the most efficient one? In other word which one demands less effort, and thus which is easier to apply? We compare now the efficiency of the two instruments.

5 Comparison of the two regulatory instrument

The goal of the regulation is to reduce the total extraction effort. We studied two types of instruments. First, we derived necessary conditions to apply a fee/subsidy scheme (an access fee for the fishery and a subsidy for those who stop fishing); in a second time we implemented a uniform (and non-transferable) quota. Each regulatory instrument must be accepted by all fishermen in the sense that they must be better-off with the regulation than under free access.

The fee/subsidy scheme excludes the less efficient fishermen until the second best or the first best level. The quota scheme limits the extraction effort (quota on input), or limits the total quantity harvested (quota on output). As a consequence, every fisherman fishes but less, even the less efficient ones. The quota should be easier to implement, in a sense that we do not have to compensate those who stop fishing as in the fee case.

Since it excludes the less efficient fishermen, the fee/subsidy dominates the quota if it implements a higher or equal effort reduction. Otherwise, the quota might be preferred despite its inability to select efficient fishermen. The proposition below shows that this case might happen.

Proposition 7 *A uniform quota might achieve a higher reduction in fishing effort than a fee/subsidy scheme.*

Proof relegated in Appendix.

We found an example where quota induces a higher diminution on aggregate effort.

6 Conclusion

In this paper, we have studied the choice of instruments to regulate an open access fishery. We have dealt with fishermen endowed with heterogenous opportunity from fishing. Those costs are private information and, therefore, not observable by the regulator. We examined successively two instruments: an access fee combined with subsidy for leaving the fishing industry and a non-transferable uniform quota. Both instruments must be accepted by all fishermen. In this set-up, the first best management of the resource requires to exclude the less efficient fishermen. It can be achieved with the fee/subsidy scheme but not with uniform quota. However, due to the above constraints, a fee/subsidy scheme could implement a higher extraction rate than the optimal allocation. And a higher reduction of fishing effort might be achieved under uniform quota than under a fee scheme at the cost of including less efficient fishermen.

The aim of this paper was to evaluate the performance of mainstream regulatory instruments in reducing over-fishing while being acceptable by fishermen. For this purpose, we have introduced heterogeneous but constant fishing costs into Gordon's static fishery model. This model captures the inefficiency dues to the lack of property rights on the fishery. The regulation mitigates this market failure highlighted by Gordon's model. Yet the static nature of the model is not satisfactory. A dynamic model is required to fully analyze the transition path from the free-access regime to a targeted efficient regulated exploitation (e.g. a first-best sustainable steady state) and, thus, provides policy recommendation on fishery regulation. This is left for future research.

APPENDIX

A Proof of Lemma 1

Step 1 For any c' and c'' such that $c' > c''$ then $x^*(c') < x^*(c'')$. Suppose it is not true: $c' > c''$ implies $x^*(c') \geq x^*(c'')$.

Suppose first that $x^*(c') > x^*(c'')$. Then $\exists \epsilon > 0$ such that $x^*(c') - \frac{\epsilon}{g(c')} > x^*(c'') + \frac{\epsilon}{g(c'')}$. Consider the allocation $\{\tilde{x}(c)\}$ defined by $\tilde{x}(c') = x^*(c') - \frac{\epsilon}{g(c')}$, $\tilde{x}(c'') = x^*(c'') + \frac{\epsilon}{g(c'')}$ and $\tilde{x}(c) = x^*(c)$ for $c \neq c', c''$. We show that it strictly improves the social welfare which contradicts that $\{x^*(c)\}$ is optimal effort allocation. Indeed, aggregate effort remains the same on both allocation: $\widetilde{X} = \int \widetilde{x}(c)dG(c) = \int x^*(c)dG(c) - \frac{\varepsilon}{g(c')}g(c') + \frac{\varepsilon}{g(c'')}g(c'') = \int x^*(c)dG(c) = X^*$. But social welfare increases:

$W(\widetilde{x}(c)) = \int \widetilde{x}[\phi(X) - c]dG(c) = \int x^*(c)[\phi(X) - c]dG(c) - \frac{\varepsilon}{g(c')}[\phi(X) - c']g(c') + \frac{\varepsilon}{g(c'')}[\phi(X) - c'']g(c'') = W(x^*(c)) + \varepsilon(c' - c'')$, since $c' > c'', W(x^*(c)) < W(\widetilde{x}(c))$.

Suppose now that $x^*(c') = x^*(c'')$. Then $\exists \epsilon > 0$ such that $x^*(c') - \frac{\epsilon}{g(c')} < x^*(c'') + \frac{\epsilon}{g(c'')}$. Consider the allocation $\{\tilde{x}(c)\}$ defined by $\tilde{x}(c') = x^*(c') - \frac{\epsilon}{g(c')}$, $\tilde{x}(c'') = x^*(c'') + \frac{\epsilon}{g(c'')}$ and $\tilde{x}(c) = x^*(c)$ for $c \neq c', c''$. We show that it strictly improves the social welfare which contradicts that $\{x^*(c)\}$ is optimal effort allocation (same reasoning as before).

Step 2 For any c', c'' and c''' such that $c''' < c' < c''$ and $0 < x(c') < \overline{x}$ then $x(c'') = 0$, $x(c''') = \overline{x}$. Suppose it is not true.

For any $c'' > c'$**,** $x(c'') > 0$. Then $\exists \epsilon > 0$ such that $x^*(c') + \frac{\epsilon}{g(c')} > x^*(c'') - \frac{\epsilon}{g(c'')}$. Consider the allocation $\{\tilde{x}(c)\}$ defined by $\tilde{x}(c') = x^*(c') + \frac{\epsilon}{g(c')}$, $\tilde{x}(c'') = x^*(c'') - \frac{\epsilon}{g(c'')}$ and $\tilde{x}(c) = x^*(c)$ for $c \neq c', c''$.We show that it strictly improves the social welfare which contradicts that $\{x^*(c)\}$ is optimal effort allocation (same reasoning as before): $W(\widetilde{c}(c)) = W(x^*(c)) + \varepsilon(c'' - c')$. Since $c'' > c'$, $W(\widetilde{c}) > W(x^*(c))$

For any $c''' < c', x(c''') < \overline{x}$. Then $\exists \epsilon > 0$ such that $x^*(c') + \frac{\epsilon}{g(c')} > x^*(c''') - \frac{\epsilon}{g(c''')}$. Consider the allocation $\{\tilde{x}(c)\}$ defined by $\tilde{x}(c') = x^*(c') - \frac{\epsilon}{g(c')}$, $\tilde{x}(c'') = x^*(c''') + \frac{\epsilon}{g(c''')}$ and $\tilde{x}(c) = x^*(c)$ for $c \neq c', c'''$. We show that it strictly improves the social welfare which contradicts that $\{x^*(c)\}$ is optimal effort allocation (same reasoning as before): $W(\widetilde{c}(c)) = W(x^*(c)) + \varepsilon(c' - c''')$. Since $c''' < c'$, $W(\widetilde{c}) > W(x^*(c))$.

B Proof of Lemma 2

Individual characterized by c^{FA} chooses $x(c) \in [0, \overline{x}]$ if and only if his rent is null:
$x(c)(\phi(X^{FA} - c)) = 0 \Leftrightarrow c = c^{FA} = \phi(X^{FA})$, and

$\forall c < c^{FA}(= \phi(X^{FA})) : \phi(X^{FA}) - c > 0$ thus $x(c) = \overline{x}$
$\forall c > c^{FA}(= \phi(X^{FA})) : \phi(X^{FA}) - c < 0$ thus $x(c) = 0$
$\forall c = c^{FA}(= \phi(X^{FA})) : \phi(X^{FA}) - c = 0$ thus $x(c) \in [0, \overline{x}]$.

C Proof of Proposition 1

Suppose it is not true.
Suppose first $X^* > X^{FA} \Leftrightarrow c^* > c^{FA}$. Recall by definition that: $c^* = X^*\phi'(X^*) + \phi(X^*)$ and $c^{FA} = \phi(X^{FA})$. For every c, $h'(X) < \phi(X)$ because $h'(X) = X\phi'(X) + \phi(X)$ and $\phi'(X) < 0$. This is particulary true where $c = c^*$. Thus,$h'(X^*) < \phi(X^*)$. As the average production function is decreasing, and since we suppose that $G(c^*) > G(c^{FA})$, $\phi(X^*) < \phi(X^{FA})$. So we have: $h'(X^*) < \phi(X^*) < \phi(X^{FA}) \Leftrightarrow h'(X^*) < \phi(X^{FA}) \Leftrightarrow c^* < c^{FA}$ witch contradicts initial assumption.
Suppose secondly that $X^* = X^{FA} \Leftrightarrow c^* = c^{FA}$. It yields that $h'(X^*) = \phi(X^{FA})$, but we saw that for every c,$h'(X) < \phi(X)$, thus $c^* \neq c^{FA}$.

D Proof of Lemma 3

Maximization program:

$$\max_{s,\tau} \int_{\underline{c}}^{c^\tau} g(c)[\bar{x}(\phi(X^\tau) - c) + \tau]dc + \int_{c^\tau}^{c^{FA}} sg(c)dc$$

such that:

$$\begin{cases} \tau G(c^\tau) + s(G(c^{FA}) - G(c^\tau)) \leq 0 & (\lambda) \\ \bar{x}[\phi(X^{FA}) - c^\tau)] - s \leq 0 & (\beta). \end{cases}$$

Before calculating the Lagragian, let's see the implication of τ and s on c^τ. From the incentive constraint (see equation 8) we obtain:

$$\frac{dc^\tau}{d\tau} = \frac{1}{\overline{x}(1 - \overline{x}g(c^\tau)\phi'(X^\tau))} > 0$$

$$\frac{dc^\tau}{ds} = -\frac{1}{\overline{x}(1 - \overline{x}g(c^\tau)\phi'(X^\tau))} = -\frac{dc^\tau}{d\tau} < 0$$

As τ is negative, an increase in τ induces a lower tax, fishermen will pay less. A decrease of the amount of τ (i.e. an augmentation of τ) increases the aggregate effort. Due to the fact that the fee is lower, fishermen have most incentive to exploit resource. $\frac{dc^\tau}{ds}$ is exactly the reverse. With multiplicators associated to each constraint, the Lagrangian of this program is:

$L = \int_{\underline{c}}^{c^\tau} g(c)[\bar{x}(\phi(X^\tau) - c)) + \tau]dc + \int_{c^\tau}^{c^{FA}} sg(c)dc + \lambda(s(G(c^\tau) - G(c^{FA}) - \tau G(c^\tau)) + \beta(s - \bar{x}(\phi(X^{FA}) - c^\tau)]$.

Necessary conditions of optimality are: $\frac{\partial L}{\partial \tau} = 0$ and $\frac{\partial L}{\partial s} = 0$. We first derive the Lagragian subject to τ, and the optimality condition says $\frac{\partial L}{\partial \tau} = 0$, it is equivalent to:

$\frac{dc^\tau}{d\tau} g(c^\tau)(\bar{x}(\phi(X^\tau) - c^\tau) + \tau) + \int_{\underline{c}}^{c^\tau} g(c)(\bar{x}\frac{dc^\tau}{d\tau}\phi'(X^\tau)g(c^\tau) + 1)dc - sg(c^\tau)\frac{dc^\tau}{d\tau} + \lambda[sg(c^\tau)\frac{dc^\tau}{d\tau} - G(c^\tau) - \tau g(c^\tau)\frac{dc^\tau}{d\tau}] + \beta\bar{x}\frac{dc^\tau}{d\tau} = 0.$

Substituting $(\bar{x}(\phi(X^\tau) - c^\tau) + \tau)$ by s (incentive constraint), and multiplying by $\frac{d\tau}{dc^\tau}$ the above equation, we obtain:

$\bar{x}G(c^\tau)\phi'(X^\tau)g(c^\tau) + G(c^\tau)\frac{d\tau}{dc^\tau} + \lambda[sg(c^\tau) - G(c^\tau)\frac{d\tau}{dc^\tau} - \tau g(c^\tau)] + \beta\bar{x} = 0,$

since $\frac{d\tau}{dc^\tau} = \overline{x}(1 - \overline{x}g(c^\tau)\phi'(X^\tau))$,

$\tau - s = \frac{\overline{x}(\beta + G(c^\tau)(1-\lambda))}{\lambda g(c^\tau)} + \bar{x}G(c^\tau)\phi'(X^\tau)$, and since $\bar{x}\phi(X^\tau) + \tau - s = \bar{x}c^\tau$, we have:

$$c^\tau = h'(X^\tau) + \frac{\overline{x}(\beta + G(c^\tau)(1-\lambda))}{\lambda g(c^\tau)}. \tag{18}$$

In a second time, we maximize with respect to s, and the first order condition is $\frac{\partial L}{\partial \tau} = 0$, with the same previous reasoning , we obtain:

$$c^\tau = h'(X^\tau) + \frac{G(c^{FA})(1-\lambda)\frac{ds}{dc^\tau}\frac{1}{\overline{x}} + G(c^\tau)(1-\lambda) + \beta(\frac{ds}{dc^\tau}\frac{1}{\overline{x}} + 1)}{\lambda g(c^\tau)}. \tag{19}$$

Equating (18) and (19), we obtain: $\beta = G(c^{FA})(\lambda - 1)$. Since $\beta \geq 0$, it yields a necessary condition on λ in order to have c^τ to be defined:

$$\beta \geq 0 \Leftrightarrow G(c^{FA})(1-\lambda) \geq 0 \Leftrightarrow \lambda \geq 1 \Leftrightarrow \lambda > 0.$$

And it yields the following expression of c^τ in function of λ or β:

$$c^\tau = h'(X^\tau) + \beta\frac{G(c^{FA}) - G(c^\tau)}{g(c^\tau)(G(c^{FA}) + \beta)}. \tag{20}$$

$$c^\tau = h'(X^\tau) + (\lambda - 1)\frac{G(c^{FA}) - G(c^\tau)}{\lambda g(c^\tau)}. \tag{21}$$

E Proof of Proposition 3

(i) $\lambda > 0$ and $\beta = 0$, thus $c^\tau = c^* = h'(X^*)$

Then regulatory instrument should satisfy, the participation constraints ($\beta = 0$), a budget balanced null ($\lambda > 0$) and incentive constraint:

$$\begin{cases} \bar{x}[\phi(X^{FA}) - \phi(X^*)] \leq \tau \leq \frac{\bar{x}[\phi(X^*)-c^*](G(c^*)-G(c^{FA})}{G(c^{FA}))} \\ \bar{x}[\phi(X^{FA}) - c^*] \leq s \leq \frac{\bar{x}[\phi(X^*)-c^*]G(c^*)}{G(c^{FA})}. \\ \tau G(c^*) + s(G(c^{FA}) - G(c^*)) = 0 \\ s - \tau = \bar{x}[\phi(X^*) - c^*] \end{cases}$$

Since budget balanced is null, it is optimal that regulator implements the highest subsidy and the lowest fee, indeed every fishermen are better off than any other (s, τ):
$\tau = \frac{\bar{x}[\phi(X^*)-c^*](G(c^*)-G(c^{FA})}{G(c^{FA}))}$ and $s = \frac{\bar{x}[\phi(X^*)-c^*]G(c^*)}{G(c^{FA})}$. Moreover fishermen must be better off than in free access, it must satisfy the participation constraint. For instance for every $c \in [c^*, c^{FA}]$, we should have:
$s \geq \bar{x}[\phi(X^{FA}) - c^*] \Leftrightarrow \frac{\bar{x}[\phi(X^*)-c^*]G(c^*)}{G(c^{FA})} \geq \bar{x}[\phi(X^{FA}) - c^*]$

$$\Leftrightarrow \frac{\bar{x}[\phi(X^{FA}) - c^*]}{\bar{x}[\phi(X^*) - c^*]} \leq \frac{X^*}{X^{FA}}.$$

(ii) $\lambda > 0$ and $\beta > 0$, thus $c^\tau = c^{SB} = h'(X^{SB}) + \beta \frac{G(c^{FA})-G(c^{SB})}{g(c^{SB})(G(c^{FA})+\beta)}$.
Regulatory instrument is implemented and such that participation constraint is bound ($\beta > 0$):

$$\begin{cases} \bar{x}[\phi(X^{FA}) - \phi(X^{SB})] = \tau \\ \bar{x}[\phi(X^{FA}) - c^{SB}] = s. \end{cases}$$

And fee/subsidy scheme is constructed such that the budget balanced is null ($\lambda > 0$): $\tau G(c^*) + s(G(c^{FA}) - G(c^*)) = 0$. Substituting by the expression of s and τ at second best, implementation requires to satisfy the following condition:

$$\frac{\bar{x}[\phi(X^{FA}) - c^{SB}]}{\bar{x}[\phi(X^{SB}) - c^{SB}]} = \frac{X^{SB}}{X^{FA}}.$$

F Proof of Proposition 4

1) $X^* < X^{SB}$

Suppose it is not true.

Suppose first $X^* > X^{SB} \Leftrightarrow c^* > c^{SB}$. Recall by definition: $c^* = h'(X^*)$ and $c^{FA} =$

$h'(X^{SB}) + \beta\frac{G(c^{FA})-G(c^{SB})}{g(c^{SB})(G(c^{FA})+\beta)}$, with $\beta\frac{G(c^{FA})-G(c^{SB})}{g(c^{SB})(G(c^{FA})+\beta)} > 0$. Recall also by definition that $h(X)$ is concave, thus:
$h'(X^*) < h'(X^{SB}) \Leftrightarrow h'(X^*) < h'(X^{SB}) + \beta\frac{G(c^{FA})-G(c^{SB})}{g(c^{SB})(G(c^{FA})+\beta)} \Leftrightarrow c^* < c^{SB}$ witch contradicts initial assumption.

2) $X^{SB} < X^{FA}$
From Proposition 3 we know that at second best: $\bar{x}[\phi(X^{FA}) - c^{SB}] = s \Leftrightarrow c^{SB} = \phi(X^{FA}) - \frac{s}{\bar{x}}$. And by definition, free access equilibrium is characterized by $c^{FA} = \phi(X^{FA})$. Thus, $c^{SB} = \phi(X^{FA}) - \frac{s}{\bar{x}} < \phi(X^{FA}) = c^{FA} \Leftrightarrow c^{SB} < c^{FA} \Leftrightarrow X^{SB} < X^{FA}$.

G Proof of Proposition 5

Rent of fisherman if he faced a tax on output $\gamma = \frac{\tau}{\overline{x}\phi(G(c(\tau)))}$:
$(1+\gamma)\overline{x}\phi(\overline{x}G(c^\tau)) - c\overline{x} = (1 + \frac{\tau}{\overline{x}\phi(G(c^\tau))})\overline{x}\phi(G(c^\tau)) - c\overline{x} = \overline{x}(\phi(G(c^\tau)) - c) + \tau$.

Rent of fisherman if he faced a tax on input $\theta = \frac{\tau}{\overline{x}}$:
$\overline{x}(\phi(\overline{x}G(c^\tau)) - c) + \theta\overline{x} = \overline{x}(\phi(\overline{x}G(c^\tau)) - c) + \frac{\tau}{\overline{x}}\overline{x} = \overline{x}(\phi(G(c^\tau)) - c) + \tau$.

H Proof of Proposition 7

Consider a particular case in a discrete case where there exist three types of agents: c_1, c_2 and c_3 ($c_1 < c_2 < c_3$), with respectively p_1, p_2 and p_3 the proportion of population of each type ($p_1+p_2+p_3 = 1$). We suppose that c_3 corresponds to the free access allocation: $c^{FA} = c_3$.

Assumptions: $p_1 = p_2 = \frac{1}{4}$ and $p_3 = \frac{1}{2}$; $p_1 + p_2 + p_3 = G(c^{FA})(= 1)$, $p_1 + p_2 = G(c_2) = \frac{1}{2}$ and $p_1 = G(c_1) = \frac{1}{4}$. $\widehat{x} = \frac{\overline{x}}{4}$, $\phi(\widehat{x}) = \phi(\frac{\overline{x}}{4}) = 3\phi(\overline{x})$ and $\phi(\frac{\overline{x}}{2}) = 2\phi(\overline{x})$.

Since $c^{FA} = c_3$, and by definition $c^{FA}(= c_3) = \phi(\overline{x}G(c^{FA}))$ we have $c_3 = \phi(\overline{x})$.
Under quota regulation and under free access regime, fishery is accessible until c^{FA}, in those cases the aggregate capacity of effort is $\widehat{x}G(c^{FA}) = \widehat{x}$. Under fee/subsidy regulation, we suppose that agents c_1 and c_2 fish, and c_3 do not. Aggregate effort is equal to $G(c_2)\overline{x} = \frac{\overline{x}}{2}$.
We want to demonstrate the possibility of a quota instrument to reduce more aggregate effort than a fee/subsdy scheme: $\widehat{x} \leq \frac{\overline{x}}{2}$, since $\widehat{x} = \frac{\overline{x}}{4}$ inequality is verified .

Incentive and acceptability constraints must be verified for both instruments, moreover we must not prevent fisherman c_2 to participate to the extraction.

Step 1 Incentive, participation constraints and budget balanced in fee case must be satisfied in both instrument regulation.

Acceptability constraint for quota, every fishermen must be better off than in free access, recall equation (17): $\underline{c} \geq \frac{\overline{x}\phi(\overline{x}G(c)) - \widehat{x}\phi(\widehat{x}G(c))}{\overline{x} - \widehat{x}}$, and with assumptions posed, we have: $\phi(\widehat{x}) \geq (\phi(\overline{x}) - c_1)\frac{\overline{x}}{\widehat{x}} + c_1 \Leftrightarrow 3\phi(\overline{x}) \geq 3\phi(\overline{x}) - 2c_1 \Leftrightarrow 2c_1 \geq 0$, it is always true.

Budget balanced constraint for fee/subsidy: $sp_3 \leq -\tau(p_1 + p_2) \Leftrightarrow s \leq -\tau$

Incentive constraint for fee/subsidy: Agents c_1 and c_2 prefer to fish than to receive a subsidy, $\overline{x}(\phi(\frac{\overline{x}}{2}) - c_2) + \tau \geq s$, and agent c_3 prefer the contrary, $\overline{x}(\phi(\frac{\overline{x}}{2}) - c_3) + \tau \leq s$.

Acceptability constraint for fee/subsidy: Agents c_1 and c_2 are better off with regulation than in free access regime, $\overline{x}(\phi(\frac{\overline{x}}{2}) - c_2) + \tau \geq \overline{x}(\phi(\overline{x}) - c_2) \Leftrightarrow \overline{x}(\phi(\frac{\overline{x}}{2}) - \phi(\overline{x})) \geq -\tau$ and agent c_3 also, $s \geq \overline{x}(\phi(\overline{x}) - c_3) \Leftrightarrow s \geq 0$, always true.

If we choose to implement the maximum tax, i.e. we bind $\overline{x}(\phi(\frac{\overline{x}}{2}) - \phi(\overline{x})) \geq -\tau$, and since $\phi(\frac{\overline{x}}{2}) = 2\phi(\overline{x})$ and $c_3 = \phi(\overline{x})$, we obtain: $-\tau = \overline{x}\phi(\overline{x})$. From budget balanced constraint we have, $s \leq \overline{x}c_3$, and from incentive constraints, $s \leq \overline{x}(c_3 - c_2)$ and $s \geq 0$. Thus a necessary condition is $0 \leq s \leq \overline{x}(c_3 - c_2)$ witch is verified since $c_3 > c_2$. All constraint are satisfied in this example.

Step 2 We must not prevent fisher c_2 to participate to extraction. If we want to prevent c_2 to fish, we violate the acceptability constraint. Suppose first the opposite situation, i.e. c_2 prefers to retire the fishery, in a second time we choose an example in order to refute it.

Budget balanced constraint for fee/subsidy: $s(p_2 + p_3) \leq -\tau p_1 \Leftrightarrow 3s \leq -\tau$

Incentive constraint for fee/subsidy: Agents c_1 prefers to fish than to receive a subsidy, $\overline{x}(\phi(\frac{\overline{x}}{4}) - c_1) + \tau \geq s$, and agent c_2 prefers the contrary, $\overline{x}(\phi(\frac{\overline{x}}{4}) - c_2) + \tau \leq s$.

Acceptability constraint for fee/subsidy: Agent c_1 is better off with regulation than in free access regime, $\overline{x}(\phi(\frac{\overline{x}}{4}) - c_1) + \tau \geq \overline{x}(\phi(\overline{x}) - c_1) \Leftrightarrow \overline{x}(\phi(\frac{\overline{x}}{4}) - \phi(\overline{x})) \geq -\tau$ and agent c_2 also, $s \geq \overline{x}(\phi(\overline{x}) - c_2)$.If we bind this constraint, we obtain: $s = \overline{x}(\phi(\overline{x}) - c_2)$.

If we choose to implement this subsidy, $s = \overline{x}(\phi(\overline{x}) - c_2)$. Since $\phi(\frac{\overline{x}}{2}) = 2\phi(\overline{x})$ and $c_3 = \phi(\overline{x})$, we obtain from incentive constraints: $2\overline{x}(\phi(\overline{x})) \leq -\tau \leq 2\overline{x}(\phi(\overline{x})) + \overline{x}(c_2 - c_1)$, and from budget balanced and participation constraint, we obtain: $3\overline{x}(\phi(\overline{x} - c_2) \leq -\tau \leq 2\overline{x}(\phi(\overline{x}))$. And a necessary condition is thus: $3\overline{x}(\phi(\overline{x} - c_2) \leq 2\overline{x}(\phi(\overline{x})) + \overline{x}(c_2 - c_1)$. Suppose the contrary: $3\overline{x}(\phi(\overline{x} - c_2) > 2\overline{x}(\phi(\overline{x})) + \overline{x}(c_2 - c_1)$, then c_2 will not prefer to receive a subsidy. It is equivalent to: $c_3 > 4c_2 - c_1$. Suppose $c_2 = \delta c_1$ and $4c_2 - c_1 = (4\delta - 1)c_1$. For instance, if we take $\delta = 2$, the solution is $(c_1, c_2, c_3) = (c_2, 2c_1, 7c_1)$, condition $c_3 > 4c_2 - c_1 \Leftrightarrow \frac{14}{3} > 1$is verified. Wehave find an example where we must not prevent c_2 to fish.

We found an application such that a uniform quota achieves a higher reduction in fishing effort than a fee/subsidy scheme.

References

[1] Ambec, S. and L. Hotte (forthcoming) "On the redistributive impact of privatizing a resource under imperfect enforcement," *Environmental and Development Economics.*

[2] Androkovich, A. and K. R. Stollery (1991) "Tax versus quota regulation: a stochastic model of the fishery," *American Journal of Agricultural Economics* **73**, 300–308.

[3] Baland, J. and P. Francois (2005) "Commons as insurance and the welfare impact of privatization," *Journal of Public Econmics* **89**, 211–231.

[4] Bjorndal, T. and G. R. Munro (1998/1999) *The economics of fisheries management: a survey.* The International Yearbook of Environmental Resource Economic.

[5] Gordon, H. S. (1954) "The econominc theory of a common property resource: the fishery," *JPE* **62**, 124–142.

[6] Hannesson, R. (1990) *The privatization of the ocean.* The MIT Press, London, England.

[7] Hartwick, J. M. and N. D. Olewiler (1998) *The economics of natural resource use.* Addison-Wesley, USA.

[8] Jensen, F. and N. Vestergaard (2003) "Prices versus quantities in fisheries models," *Land Economics* **79**, 415–425.

[9] Johnson, R. N. and G. D. Libecap (1982) "Contracting problem and regulation: The case of fishery," *AER* **72**, 1005–1022.

[10] Pearse, D. W. and R. K. Turner (1990) *Economics of natural resources environment.* The Johns Hopkins University Press, Baltimore.

[11] Stevenson, G. (1991) *Common property economics.* Cambridge Univerrsity Press, New York, New York, USA.

Figure 1: The first best and free access regimes.

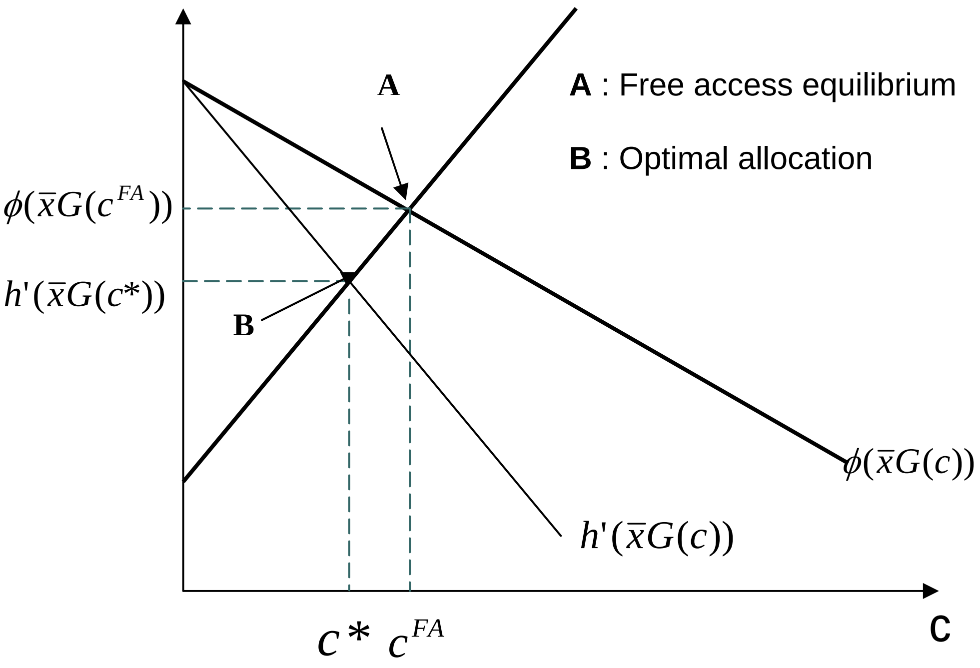

Figure 2: Surplus under free access and fee/subsidy scheme.

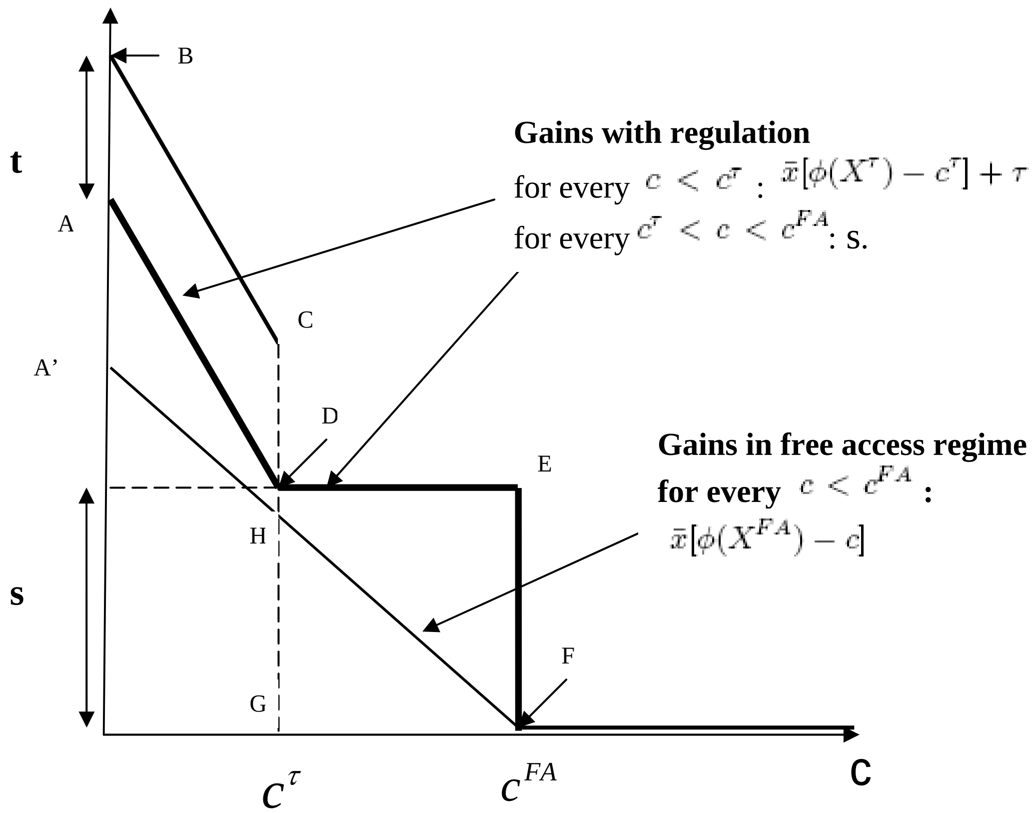

Figure 3: Regulating with quota on output.