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# Ecosystem considerations in a second-best world

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## Abstract

Species' interactions and the involvement of fishermen in several fisheries may not be properly accounted for by regulatory schemes, thus making regulation suboptimal. Being the only implementable instruments, the degree of inefficiency of three second-best instruments is assessed (by using a bioeconomic multispecies model) in terms of their ability to get close to socially optimal effort and stock levels. The type of regulation and the existing biological interaction are also shown to result in different impacts on effort re-allocation: a specific regulation does not necessarily increase the pressure on the unregulated species. Finally, we discuss how the choice of which second-best policy to implement is situation-specific.

*JEL Classification:* Q22, Q28.

*Keywords:* bioeconomic model, second-best management, effort allocation, multispecies interactions.

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# 1 Introduction

The last reports on the status of the world's fisheries point out the unceasing decline of marine resources. Indeed, the 2010 FAO status report [14] shows that 53% of monitored fish stocks are fully exploited, while respectively 28% and 3% are overexploited and depleted. Moreover, the 2010 UNEP report [31] claims that there will be no fish stocks left to catch by 2050 in the world's oceans. This alarming situation questions the efficiency of fisheries management and highlights that measures taken so far may be suboptimal. Although existing work has found that efficiency requires a minimal market-related information (Arnasson [3]) or depends on ecosystem-based considerations (Grafton *et al.* [19]), there have been no attempt to assess their role in management failure. In this paper, we especially try to examine to which extend fishermen's behavior, given their potential implications in different fisheries and given the existence of ecological interactions, may impact on the efficiency of some market-based instruments.

A substantial literature has emerged on management instruments like restrictions on fishing time, gear restrictions, entry license, (transferable) catch quotas, landing fees or effort taxes (among others, Anderson [2], Costa Duarte [11], Weitzman [35]). Market-based instruments have been studied extensively since they potentially may lead to improve on the efficiency of fisheries management (Cunningham *et al.* [12]). However, many FAO reports [14] show that most fisheries are still overexploited, which raises a legitimate question about the measures implemented. Some studies highlight that government may deliberately implement suboptimal fisheries management because of issues such as the social climate, which may impede on the performance of market-based instruments (Arnasson [4]). As such, these schemes are typically second-best. Karpoff [22] stresses that, if existing regulatory practices are interpreted as the outputs of a political system used to redistribute wealth among fisheries, then their persistent suboptimality may be rationalized. Others point out the multi-purpose nature of fishing activities and that priority may be employment rather than economic efficiency considerations (Hanesson for the Norwegian case [21] or Boude *et al.* [7] for the case of the European community).

Apart from these socio-economic hurdles, some technical or practical arguments may be raised to understand the failure of market-based instruments to rebuilt resource stocks. First, Arnason [3] highlights that success depends on the level of information available to the resource manager implementing management instruments. Individual transferable quotas may lead to efficiency under minimal market-related information, while taxes/subsidies

require a large amount of information on stocks. In this study, we claim that regulators often overlook that fishermen may avoid regulations since they may be involved in several fisheries. Moreover, even if scientists now advocate an ecosystem-based approach to fisheries (Grafton *et al.* [19]) in order to deal with ecologically-based externalities, biological interactions are often ignored, and a large part of the literature still focuses on single-species models to design management tools. All these reasons may, at least partially, explain why most of regulatory measures are not sufficient and suboptimal. The purpose of this paper is to study the effects of such second-best management systems, and to assess how they depend on the existing biological relationship between species and on the economic characteristics of fisheries driving effort allocation.

Issues of second-best management of interdependent species have received some recent attention in the literature. Ashe *et al.* [5] empirically show that lower quotas induce fishermen to target unregulated species. Boncoeur *et al.* [6] show that the biological consequences of a marine protected area depends on the biological relationship between species. Quaas and Requate [25], or Agar and Sutinen [1] stress that myopic management of a species ignoring potential spillovers may negatively affect unregulated species or more generally affect the success of the recovery process. All these results suggest that one should refine the conclusions concerning the effect of second-best management on resource stocks; no study, to the best of our knowledge, explains precisely how the type of biological interaction and the ability to reallocate effort between fisheries affect the degree of inefficiency of regulation schemes. We aim at filling this gap by analyzing fishermen's responses to suboptimal regulatory systems and their incentives to reallocate fishing efforts between ecologically-interdependent species.

To proceed with the analysis, we consider a selective fisheries model, where a fleet harvests two interdependent fish species and boats have to be allocated between both targeted species. The allocation of effort is especially driven by market prices. We introduce three types of second-best taxation schemes, ignoring either biological interactions or the fact that fishermen involved in the fisheries may reallocate their effort from one sector to another. More specifically, we use one landing tax (and one effort-based tax) focused on only one species (or sector), thus not accounting for biological interactions. We then introduce a fleet-based tax that ignores the potential for effort redirection between the two fisheries. Moreover, different types of ecological interactions are considered. The predator-prey relationship has been mostly analyzed in the literature (e.g. May *et al.* [23], Hannesson

[20], Mesterton-Gibbons [24], Costa Duarte [11], Ussif and Sumaila [27]). A few contributions consider other types of interactions, highlighting the specific features of the socially optimal policy (see Flaaten [16] for competitive species, von dem Hagen and Wacker [32] or Wacker [33] for mutualistic resources, and Fleming and Alexander [17] for a general overview). By contrast, we consider all these different types of interaction within the same setting.

Our contribution is three-fold. We first assess the impact of such management tools on the size of the fleet and on the allocation of boats between species. An interesting counter-intuitive result is that fishermen do not necessarily re-allocate their effort from the regulated species/fisheries to the unregulated one. This reallocation is driven by the ecological relationship and economic returns. For instance, we show that the pressure on the unregulated fisheries increases for mutualistic relationships under species-specific taxation, that effort re-allocation is ambiguous under fleet-based taxation, and that pressure decreases under the three taxation schemes when species are competitive.

Second, we investigate how far away from the socially optimal outcome those suboptimal measures could be. We surprisingly show that, under sectoral regulation, subsidies may be second-best due to biological interactions, which contributes to widening the gap with the socially optimal stock levels. Moreover, certain cases are highlighted where a species-specific regulation makes things worse: compared to the case of open access, this regulatory instrument actually increases the gap with respect to socially optimal management. The comparison is more ambiguous regarding the fleet-based taxation, and depends on biological parameters. Finally, we characterize the type of instrument that enables to get closest to the socially optimal levels, and we show that conclusions depend mainly on the type of biological interaction.

The model is introduced in Section 2. The basics of the model are introduced in Section 2, the open access equilibrium and socially optimal policy are characterized in Section 3. Section 4 is focused on management policies: the consequences of species-specific and effort management are analyzed in sub-sections 4.1 and 4.2, respectively. Section 5 concludes.

## 2 A selective multi-species model

We assume that at every time  $t$  a global effort level  $E_t$  must be allocated between two fishing activities.<sup>1</sup> If one interprets the global effort level as the

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<sup>1</sup>Global effort denotes the overall capacity of fishing in all fisheries. It could refer to the total number of boats or gears, to the global size of the fleet or to any other inputs.

size of the fleet, a boat (seen as an effort unit) is used to harvest one or the other fish species: at time  $t$  a proportion  $\lambda_t \in (0, 1)$  of effort of the industry is allocated to harvest species  $x$  and the remaining share  $(1 - \lambda_t)$  is allocated to harvest species  $y$ . We assume a simple form of harvest function where ( $\theta$  denoting the catchability coefficient): (i)  $\lambda_t \theta E_t x_t$  denotes the quantity of the  $x$ -species harvested at time  $t$  and (ii)  $(1 - \lambda_t) \theta E_t y_t$  corresponds to the quantity of  $y$ -species that is harvested. Still interpreting the global effort level as the overall number of boats (at time  $t$ ), we can think of  $\lambda E$  and  $(1 - \lambda)E$  as (respectively) the size of the  $x$ -species and  $y$ -species fishery sectors. The industry faces the following instantaneous profit function:

$$\Pi_t = p_x \lambda_t \theta E_t x_t + p_y (1 - \lambda_t) \theta E_t y_t - w E_t \quad (1)$$

where  $p_i$  is the price of species  $i = \{x, y\}$  and  $w$  is the unit cost of effort  $E$ .

Under open-access the industry faces a free entry-exit procedure that depends on the profit level. Following Smith ([29], [30]), we assume the level of fishing effort changes continuously over time according to the following equation:<sup>2</sup>

$$\dot{E} = [p_x \theta \lambda_t x_t + p_y \theta (1 - \lambda_t) y_t - w] E_t \quad (2)$$

Finally, we assume the following population dynamics:

$$\dot{x} = x_t (\alpha_x - a_x x_t + \gamma_x y_t - \lambda_t \theta E_t) \quad (3)$$

$$\dot{y} = y_t (\alpha_y - a_y y_t + \gamma_y x_t - (1 - \lambda_t) \theta E_t) \quad (4)$$

where  $a_x$  and  $a_y$  are intraspecific competition (positive) parameters, and the sign of interspecific interaction parameters  $\gamma_i$  ( $i = x, y$ ) depends on the ecological relationship: predation, competition or mutualism. The different cases are summarized in Table 1:

In the case of predator-prey interactions, the intrinsic growth rate for the high trophic level  $i$  is assumed to be equal to zero,  $\alpha_i = 0$ , since the growth of the predator population depends on the prey only.

We assume two conditions to ensure the stability of the system and the coexistence of species under the different types of interactions. First, we

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<sup>2</sup>The temporal change in effort is usually assumed to be proportional to the net returns (Smith ([29],[30])). Here, we assume that the rate of proportionality (the entry/exit coefficient) is equal to 1.

Table 1: Populations Interactions

	$\gamma_x > 0$	$\gamma_x < 0$
$\gamma_y > 0$	Mutualism	Prey-predator relationship with $x$ the prey
$\gamma_y < 0$	Prey-predator relationship with $x$ the predator	Competition

require that the standard Hawkins-Simon condition<sup>3</sup> is satisfied [33]:

$$a_x a_y - \gamma_x \gamma_y > 0 \quad (5)$$

This condition requires that the combined intraspecific competition has to be stronger than the combined ecological interaction: otherwise, for instance, mutualistic species would grow indefinitely. Second, following Chesson [8], we require that intra-species competition regulates the growth resulting from spillover effects. That is, for  $i, j = x, y, i \neq j$ , we have:

$$a_i \alpha_j + \gamma_j \alpha_i > 0. \quad (6)$$

These conditions are necessary and sufficient to ensure the existence and stability of an interior steady state of the dynamical system without harvest (see Chesson [8]), that is:

$$\tilde{x} = \frac{a_y \alpha_x + \alpha_y \gamma_x}{a_x a_y - \gamma_x \gamma_y}; \quad \tilde{y} = \frac{a_x \alpha_y + \alpha_x \gamma_y}{a_x a_y - \gamma_x \gamma_y}. \quad (7)$$

In the case of a predator-prey relationship, the conditions hold automatically at the equilibrium regarding the prey species, but condition (6) must be satisfied to ensure that the prey coexists with the predator.

For a given allocation of effort between the two fishing activities (that we denote  $\lambda$ ) we can now characterize the interior bioeconomic equilibrium (that is, where the two species coexist) by setting  $\dot{x} = \dot{y} = \dot{E} = 0$ , and we obtain:

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<sup>3</sup>This condition is commonly used to characterize an economy in which production growth is proportional to the production levels. It is derived from the input-output analysis.

$$\begin{aligned}
x^* &= \frac{p_y \theta (1 - \lambda) [\alpha_x (1 - \lambda) - \alpha_y \lambda] - w [(1 - \lambda) \gamma_x + \lambda \gamma_y]}{\theta [p_y (1 - \lambda) (a_x p_y (1 - \lambda) - a_y \theta) - \lambda p_x ((1 - \lambda) \gamma_x + \lambda \gamma_y)]} \\
y^* &= \frac{w (a_x (1 - \lambda) - a_y \lambda) - \lambda p_x \theta [\alpha_x (1 - \lambda) \alpha_x - \lambda \alpha_y]}{\theta [p_y (1 - \lambda) (a_x p_y (1 - \lambda) - a_y \theta) - \lambda p_x ((1 - \lambda) \gamma_x + \lambda \gamma_y)]} \\
E^* &= \frac{\lambda p_x \theta (\alpha_x \gamma_y - \alpha_y \gamma_x) + \theta p_y (1 - \lambda) (a_y \alpha_x - a_x \alpha_y) - w (a_x \gamma_y - a_y \gamma_x)}{\theta^2 [p_y (1 - \lambda) (a_x p_y (1 - \lambda) - a_y \theta) - \lambda p_x ((1 - \lambda) \gamma_x + \lambda \gamma_y)]}
\end{aligned}$$

We have the following property:

**Proposition 1** *Under conditions (5) and (6), the interior bioeconomic equilibrium,  $(x^*, y^*, E^*)$ , is a saddle point.*

We just prove the stability of the steady state. In the next section we will build on this preliminary analysis in order to define the targeted bioeconomic equilibrium.

### 3 Open access equilibrium versus socially optimal outcome

In Section 3 we characterize the *targeted bioeconomic equilibrium*, where the effort allocation between species will be driven by profit maximization. Then we characterize the socially optimal policy, and derive some preliminary implications regarding the comparison of the size of the different sectors.

#### 3.1 The targeted bioeconomic equilibrium

So far we characterized the long-run resource stock and effort levels for a given effort allocation. To close the characterization of the open-access bioeconomic equilibrium, the model requires a condition regarding the optimal effort allocation between the two species, which aims at maximizing the instantaneous fishing profit (1). Interpreting the situation as one where a fleet is allocated between the different fishing activities, conditions  $\dot{x} = \dot{y} = \dot{E} = 0$  characterize the long run open access stock and effort equilibrium levels, and we finally need to characterize the open access equilibrium allocation. Following Costa Duarte [11], this final condition is related to the allocation decision variable  $\lambda$ , and states that the marginal revenue per unit of effort is the same for both species. We have:

$$\frac{\partial \Pi}{\partial \lambda} = 0 \Leftrightarrow \theta E_t (p_x x_t - p_y y_t) = 0 \tag{8}$$



There is no incentive at the open access equilibrium to allocate an extra unit of effort to harvest one particular species. The extra revenue from fishing species  $x$  (because one additional vessel will be allocated to target it) exactly covers the marginal loss of revenue coming from a decrease in the effort allocation to harvest the other one. We obtain a *targeted bioeconomic equilibrium*, which long-run stock levels are given by:

$$\hat{x} = \frac{w}{\theta p_x} ; \hat{y} = \frac{w}{\theta p_y} \quad (9)$$

We then deduce the effort level and share allocation (with  $\alpha_i = 0$  if the  $i$ -species is the predator):

$$\hat{E} = \frac{\alpha_x + \alpha_y + \hat{x}(\gamma_y - a_x) + \hat{y}(\gamma_x - a_y)}{\theta} \quad (10)$$

$$\hat{\lambda} = \frac{\alpha_x + \alpha_y - a_x \hat{x} + \gamma_x \hat{y}}{\alpha_x + \alpha_y + \hat{x}(\gamma_y - a_x) + \hat{y}(\gamma_x - a_y)} \quad (11)$$

as well as:

$$\hat{\lambda} \hat{E} = \frac{\alpha_x - a_x \hat{x} + \gamma_x \hat{y}}{\theta} ; (1 - \hat{\lambda}) \hat{E} = \frac{\alpha_y - a_y \hat{y} + \gamma_y \hat{x}}{\theta} \quad (12)$$

The above characterizations highlight that the equilibrium global effort level  $\hat{E}$  and the sectoral allocation depend explicitly on the ecological relationships.

### 3.2 The social optimum

In this section, we assume that a social planner chooses the social optimal effort level and share allocation to maximize the present value of net social benefits with respect to population dynamics (3) and (4), with  $\delta$  denoting the discount rate. The planner's problem is then:

$$\begin{aligned} \max_{E, \lambda} \int_0^{\infty} (p_x \theta \lambda_t E_t x_t + p_y \theta (1 - \lambda_t) E_t y_t - w E_t) \exp^{-\delta t} dt \\ \dot{x} = x_t (\alpha_x - a_x x_t + \gamma_x y_t - \theta \lambda_t E_t) \\ \dot{y} = y_t (\alpha_y - a_y y_t + \gamma_y x_t - \theta (1 - \lambda_t) E_t) \end{aligned}$$

The current-value Hamiltonian is as follows:

$$H(x_t, y_t, \mu_{xt}, \mu_{yt}) = p_x \theta \lambda_t E_t x_t + p_y \theta (1 - \lambda_t) E_t y_t - w E_t + \mu_{xt} x_t (\alpha_x - a_x x_t) + \gamma_x y_t - \theta \lambda_t E_t + \mu_{yt} y_t [\alpha_y - a_y y_t + \gamma_y x_t - \theta (1 - \lambda_t) E_t]$$

For an interior solution the optimality conditions are:

$$\frac{\partial H}{\partial E} = p_x \theta \lambda_t x_t + p_y \theta (1 - \lambda_t) y_t - w - \mu_{xt} \theta \lambda_t x_t - \mu_{yt} \theta y_t (1 - \lambda_t) = 0 \quad (13)$$

$$\frac{\partial H}{\partial \lambda} = \theta E_t (p_x x_t - p_y y_t) - \theta E_t (\mu_{xt} x_t - \mu_{yt} y_t) = 0 \quad (14)$$

$$\dot{\mu}_x = \mu_{xt} [\delta - \alpha_x + 2a_x x_t - \gamma_x y_t + \lambda_t \theta E_t] - \mu_{yt} \gamma_y y_t - p_x \theta \lambda_t E_t \quad (15)$$

$$\dot{\mu}_y = \mu_{yt} [\delta - \alpha_y + 2a_y y_t - \gamma_y x_t + \theta (1 - \lambda_t) E_t] - \mu_{xt} \gamma_x x_t - p_y \theta (1 - \lambda_t) E_t \quad (16)$$

From conditions (13) and (14), the shadow prices of the prey species,  $\mu_x$ , and that of the predator species,  $\mu_y$ , are equal to the average of the monetary value of the biomass stock level in the optimum, given the catchability coefficient, net of the unit effort cost,  $\bar{\mu}_x = \frac{p_x \theta \bar{x} - w}{\theta \bar{x}}$  and  $\bar{\mu}_y = \frac{p_y \theta \bar{y} - w}{\theta \bar{y}}$ . Equations (15) and (16) are modifications of the well-known “fundamental equation” (Clark [9]). Looking for the long-run outcome, we set equation (15) equal to zero; then, using (13) and (14) yields:

$$\delta = \alpha_x - 2a_x x_t + \gamma_x y_t - \frac{\lambda \theta E (\mu_x - p_x)}{\mu_x} + \frac{\mu_y \gamma_y y_t}{\mu_x} \quad (17)$$

The first two terms on the RHS of equation (17) are the standard steady-state conditions. The last term models the two-species interaction and measures the sensitivity of the growth of population  $y$  to a change in population  $x$ : the feedback effect on productivity of the species results in an additional marginal cost (or value depending on the type of interaction) of harvesting species  $x$ . A similar condition holds for the second species:

$$\delta = \alpha_y - 2a_y y_t + \gamma_y x_t - \frac{(1 - \lambda) \theta E (\mu_y - p_y)}{\mu_y} + \frac{\mu_x \gamma_x x_t}{\mu_y} \quad (18)$$

From conditions (13) to (16), we obtain the following long-run social optimum:

**Proposition 2** *The long run interior socially optimal policy is given by the following conditions:*

$$\begin{aligned}\bar{E} &= \frac{\alpha_x + \alpha_y + \bar{x}(\gamma_y - a_x) + \bar{y}(\gamma_x - a_y)}{\theta} ; \quad \bar{\mu}_x = \frac{p_x \theta \bar{x} - w}{\theta \bar{x}} \\ \bar{\lambda} &= \frac{\alpha_x - a_x \bar{x} + \gamma_x \bar{y}}{\alpha_x + \bar{x}(\gamma_y - a_x) + \bar{y}(\gamma_x - a_y) + \alpha_y} ; \quad \bar{\mu}_y = \frac{p_y \theta \bar{y} - w}{\theta \bar{y}} \\ 2p_x \theta a_x \bar{x}^2 + \bar{x} [p_x \theta (\delta - \alpha_x) - \bar{y} \theta (p_x \gamma_x + p_y \gamma_y) + w(\gamma_y - a_x)] - \delta w &= 0 \\ 2p_y \theta a_y \bar{y}^2 + \bar{y} [p_y \theta (\delta - \alpha_y) - \bar{x} \theta (p_y \gamma_y + \gamma_x p_x) + w(\gamma_x - a_y)] - \delta w &= 0\end{aligned}$$

According to Dockner [13], we can analyze the stability properties of this equilibrium outcome. We find that:

**Proposition 3** *Under conditions (5) and (6), the equilibrium,  $\{\bar{x}, \bar{y}, \bar{E}, \bar{\lambda}\}$ , is a saddle point.*

We thus know that there exists a trajectory which converges to the long-run outcome.

Before concluding this section, we compare the socially optimal outcome and the targeted open access equilibrium. We can use the expression of the two shadow prices,  $\bar{\mu}_x$  and  $\bar{\mu}_y$ , to compare the stock levels under sole ownership and open access described by equations (9):

$$\bar{x} - \hat{x} = \frac{\bar{\mu}_x w}{\theta p_x (p_x - \bar{\mu}_x)} > 0 ; \quad \bar{y} - \hat{y} = \frac{\bar{\mu}_y w}{\theta p_y (p_y - \bar{\mu}_y)} > 0 \quad (19)$$

Inequalities (19) imply that open access leads to the over-exploitation of both species. Furthermore, the difference between stock levels under the two extraction regimes depends only on the shadow price associated with the resource considered. This suggests that the regulation of both species is required in order to implement the first-best outcome.

However, the over-exploitation of both resources does not result from excessively high fishing pressure. This is highlighted by the comparison of sectoral sizes:

$$\bar{\lambda} \bar{E} - \hat{\lambda} \hat{E} = \frac{-a_x (\bar{x} - \hat{x}) + \gamma_x (\bar{y} - \hat{y})}{\theta} \quad (20)$$

$$(1 - \bar{\lambda}) \bar{E} - (1 - \hat{\lambda}) \hat{E} = \frac{-a_y (\bar{y} - \hat{y}) + \gamma_y (\bar{x} - \hat{x})}{\theta} \quad (21)$$

The comparison of sectoral sizes depends on the magnitude of over-exploitation and on the ecological parameters modeling intra- and inter-specific competition. The general conclusion can be stated as follows:

**Proposition 4** *Depending on the type of biological interactions and the relative strengths of intra versus inter-specific competition for both species, the size of the open-access sectors might be smaller than under socially optimal management.*

Without interaction,  $\gamma_i = 0$  with  $i = \{x; y\}$ , the size of sectors under open access is obviously larger than under socially optimal management. When interacting species are considered, this conclusion does not hold generically. Too much effort will be put on harvesting competitive species under open access, as it intuitively expected. However, for the other types of relationships, this now depends on the relative strengths of intra versus inter-specific relationships. With prey-predator interactions, the prey-fisheries sector is *always* larger under open access, while the predator-fisheries sector may be smaller under open access if the dependence on the prey offsets the intra-species competition. The comparison is more ambiguous for mutualistic species. Nevertheless, we notice that the pressure on a species will be higher under the socially optimal regime if inter-species interaction offsets this species' internal competition. Moreover, the fishing pressure cannot be higher (under socially optimal management) for both species.

To conclude this result highlights that, depending on species' interactions, systematic decrease in the fishing pressure might not necessarily constitute evidence of more efficient regulation practices as it could be implemented under suboptimal management. This further raises the question of induced effort reallocation.

## 4 Management policies

The impact of different second-best management policies is now discussed. We introduce specifically a species-specific landing and effort tax, and a global fleet-based regulation. This will enable us to assess economic efficiency of each instrument and their potential for resource conservation. We will first investigate the impact of taxation to determine how fishing effort is reallocated between both existing activities. We then define tax levels under these suboptimal conditions. This will enable us to finally analyze the extent of regulation's impact.

### 4.1 Species/sector-specific regulation

We assume that a fishery manager imposes either a species-specific landing tax, say on  $x$ , which is denoted by  $\tau_x$ , or a species-specific effort tax, denoted

by  $\tau_f$ . In the rest of the paper, the first (respectively, second) scheme will be referred to as the landing (respectively, sector-specific) tax. Moreover, we will refer to regulated (resp. unregulated) species or sector for any type of regulatory system. Regulated fishermen still act as if they had open access to each fishery, but the tax will induce them to modify effort and harvest. In the first scenario, the introduction of such a fee will modify equation (8) as:  $(p_x - \tau_x)x_t - p_y y_t = 0$ . In the second one, the sector-specific fee will modify condition (2) as :  $p_x \lambda \theta x + p_y (1 - \lambda) \theta y = \lambda(w + \tau_w) + (1 - \lambda)w$ . We obtain the corresponding expressions of the equilibrium stock levels:

$$\hat{x}_{\tau_x} = \frac{w}{\theta(p_x - \tau_x)}, \quad \hat{x}_{\tau_f} = \frac{w + \tau_f}{\theta p_x},$$

while the stock of unregulated species  $y$  remains at its open access level (as given by (9)). We notice that the stock level of species  $x$  might increase or decrease (depending on whether the fee corresponds to a tax or a subsidy).

We first analyze the impact of such regulatory structures on fishermen behavior: we assess the effect of changes in the tax value on the long-run effort level, on its allocation between fisheries sectors, and on the size of each sector. This actually depends on the effect of stock variations (induced by the change in the fee value) on each specific variable,  $\hat{Z} = \{\hat{E}; \hat{\lambda}; \hat{\lambda}\hat{E}; (1 - \hat{\lambda})\hat{E}\}$ :

$$\frac{\partial \hat{Z}_{\tau_i}}{\partial \tau_i} = \frac{\partial \hat{Z}_{\tau_i}}{\partial x} \cdot \frac{\partial \hat{x}_{\tau_i}}{\partial \tau_i} \quad \text{with } i = \{x, f\}$$

Let us assume that the fee is a tax<sup>4</sup>: as such we know that it positively affects the stock level. The qualitative impact of the instrument will thus only depend on the stock effect, which is characterized as follows:

$$\frac{\partial \hat{E}}{\partial x} = -\frac{(a_x - \gamma_y)}{\theta}; \quad \frac{\partial \hat{\lambda}}{\partial x} = \frac{(a_x a_y - \gamma_x \gamma_y)(\hat{y} - \tilde{y})}{(\theta E)^2} \quad (22)$$

$$\frac{\partial(\hat{\lambda}\hat{E})}{\partial x} = -\frac{a_x}{\theta}; \quad \frac{\partial((1 - \hat{\lambda})\hat{E})}{\partial x} = \frac{\gamma_y}{\theta} \quad (23)$$

Conditions (22) and (23) highlight that the impact of such regulatory schemes depends on the intensity of intra/interspecific relations. More specifically, the

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<sup>4</sup>This implies that the conclusions will be reversed if one does the comparative statics assuming that the initial fee is a subsidy.

effect on the allocation share depends on the difference between the stock level of the unregulated species ( $\hat{y}$ ) and its level without harvest ( $\tilde{y}$ ). Following the intuition, we may expect that the potential marginal effort value of this stock is higher than the marginal cost (otherwise there is no reason to catch this species). Consequently, we may expect that  $\hat{y} - \tilde{y}$  be negative, meaning that a higher population density decreases (respectively, increases) the number of boats that will be assigned to the regulated (respectively, unregulated) sector. Despite the fact that effort redirection is straightforward, it does not mean that the pressure on unregulated species increases. The resulting impact on the size of both sectors also depends on changes in the global effort level. The net effect depends on both inter and intra-species relationships. More specifically, the net effect on the regulated sector will always be negative as it only depends on the intra-species relationships. By contrast, it depends on interspecies relationship for the unregulated sector. For instance, for competitive species, global effort level decreases enough so that it offsets the increase in the effort share allocated to this sector ( $1 - \lambda$ ). This implies that the decrease in the global effort level is the dominant effect compared to effort reallocation to the unregulated sector. By contrast, with mutualistic species, we may observe an decrease in the global effort level, while the number of boats allocated to the unregulated sector increases. This thus implies that effort reallocated to the unregulated sector is enough to counterbalance the increase in the global effort level.

**Proposition 5** *A selective regulatory scheme always reduces the pressure on the unregulated species under competitive relationships (due to the change in the fleet level).*

*However, the pressure increases for mutualistic relationships because of a strong effort redirection from the regulated sector to the unregulated sector. For prey-predator relationship, results are similar to the competitive case if the unregulated species is the predator, and are similar to the case of mutualistic species otherwise.*

Table 2 summarizes the conclusions for a tax on either species  $x$  or the  $x$ -species sector.

Table 2: Impact of a  $x$ -species/sector-specific tax

	Predation	Competition	Mutualism
Share ( $\lambda$ )	+/-	+/-	+/-
Total Effort ( $E$ )	if $x$ is prey: +/- if $x$ is predator: -	-	+/-
$x$ -species fishery activity ( $\lambda E$ )	-	-	-
$y$ -species fishery activity ( $(1 - \lambda)E$ )	if $y$ is prey: - if $y$ is predator: +	-	+

If we now contrast these results with conditions (20) and (21), we notice that a selective taxation scheme may increase the difference between the size of a given sector under optimal management and under regulation. This is specifically the case when biological parameters are such that the socially optimal levels are higher than under open access (since taxation decreases the pressure on the regulated species). This logically raises the question about the efficiency of these policies. We thus now assess the relative efficiency of such instruments by measuring how far away from the corresponding first-best level a selective management policy could be, given that this policy is only second-best. Let us first characterize the fees that either restore the optimal stock level of the regulated species,  $\hat{x}_{\tau_x} = \bar{x}$ , or align the sectoral allocation with the socially optimal level (when using a sector-specific tax),  $\hat{\lambda}_{\tau_f} \hat{E}_{\tau_f} = \bar{\lambda} \bar{E}$ . The first immediate conclusion is that a fishery manager willing to impose a fee on landing species  $x$  to implement the socially optimal stock level  $\bar{x}$  will use a tax rate equal to its own shadow price:  $\tau_x^* = \bar{\mu}_x > 0$ . If the manager wants to regulate the proportion of effort level dedicated to species  $x$ , the value of this fee is equal to the following expression<sup>5</sup>:

$$\tau_f^* = \frac{\theta p_x [a_x(\bar{x} - \hat{x}) - \gamma_x(\bar{y} - \hat{y})]}{a_x} = \frac{\theta^2 p_x (\hat{\lambda} \hat{E} - \bar{\lambda} \bar{E})}{a_x} \quad (24)$$

Equation (24) shows that the fiscal scheme depends on the difference between the size of the targeted sector under open access and its optimal level. According to proposition 4, it can thus take the form of a tax or a subsidy. More specifically, we derive the following conclusions:

<sup>5</sup>The proof of this characterization is provided in the proof of Proposition 6 in the appendix.

**Proposition 6** *In the case of sector-specific regulations, the manager should provide a subsidy to the targeted sector if the targeted species is a predator highly dependent on the prey-species or for mutualistic species with a high degree of interspecific dependency.*

*In all other cases, the manager should tax the targeted sector.*

We can now analyze if these regulatory schemes enable the regulator to reduce the difference between sectoral sizes under open access and under a socially optimal regime. This will provide a measure of the relative efficiency of these two management policies.<sup>6</sup> Let us compute again equations (20) and (21) while accounting for taxation.

$$\begin{aligned}\bar{\lambda}\bar{E} - \hat{\lambda}_{|\tau_x}\hat{E}_{|\tau_x} &= \frac{\gamma_x(\bar{y} - \hat{y})}{\theta} ; (1 - \bar{\lambda})\bar{E} - (1 - \hat{\lambda}_{|\tau_x})\hat{E}_{|\tau_x} = -\frac{a_y(\bar{y} - \hat{y})}{\theta} \\ \hat{\lambda}_{|\tau_f}\hat{E}_{|\tau_f} &= \bar{\lambda}\bar{E} ; (1 - \bar{\lambda})\bar{E} - (1 - \hat{\lambda}_{|\tau_f})\hat{E}_{|\tau_f} = -\frac{(\bar{y} - \hat{y})(a_x a_y - \gamma_x \gamma_y)}{a_x \theta}\end{aligned}$$

We notice that only the regulated sector reaches its optimal size under a sector-based regulation. It is easily checked that the unregulated sector is always larger than its optimal size because of a lack of self-regulation within a given species, which yields a higher population density. This in turn allows for higher harvest levels. The gap between the size of the regulated sector (under a landing tax) and its optimal level results from the lack of interaction of the regulated species with the unregulated one (since the stock level is smaller under open access). The specific size of the gap depends on the type of ecological interactions.

If we now contrast these differences with equations (20) and (21), we can assess whether these instruments actually decrease the gap between the size of the regulated (respectively, unregulated) sector under both management regimes (compared to the case of no regulation). Proposition 7 highlights that these mechanisms might actually have an unexpected, negative impact.

**Proposition 7** *An effort-specific tax,  $\tau_f$ , closes the gap between the size of the sector (targeted by regulation) under socially optimal and regulated open access managements. It has an ambiguous impact regarding the unregulated sector.*

*A species-specific landing tax,  $\tau_x$ , only partially closes this gap for both sectors (i) when species are competitive, (ii) if the regulated species is a prey,*

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<sup>6</sup>We do not need to analyze the effect on  $E$  or on  $\lambda$  in order to derive results on sectors. For instance, regarding the species-specific tax, if  $(1 - \bar{\lambda})\bar{E} < (1 - \hat{\lambda}_{|\tau_x})\hat{E}_{|\tau_x}$  because  $\hat{E}_{|\tau_x} > \bar{E}$  and species are mutualistic, then one necessarily has  $\bar{\lambda} > \hat{\lambda}_{|\tau_x}$ .



or (iii) for mutualistic species which differential between the intensity of intra and interspecific relationship is sufficiently large. Otherwise, the gap increases.

Proposition 7 highlights that these mechanisms enable to get close to the socially optimal outcome (in terms of the size of fisheries sectors) for some species, but that there are cases where they could also make the situation worse. As a result, these mechanisms should be implemented (when first-best management is not feasible) *only* in particular situations.

Moreover, it is interesting to notice that there exist some cases where these mechanisms could further decrease the effort level dedicated to one sector in situation where the pressure under open access was initially higher than that under socially optimal management (and following regulation, the pressure is further decreased). This is especially the case for mutualistic species where the degree of self-retention is sufficiently high.

We finally focus on the choice between both instruments. We actually claim that a sector-specific regulation is more effective than a species-specific taxation regarding the evolution of the regulated fisheries since this sector becomes optimal. Regarding the unregulated sector, once again the conclusion depends on the type of biological interactions. We have the following expressions:

$$\left[ (1 - \bar{\lambda})\bar{E} - (1 - \hat{\lambda}_{|\tau_x})\hat{E}_{|\tau_x} \right] - \left[ (1 - \bar{\lambda})\bar{E} - (1 - \hat{\lambda}_{|\tau_f})\hat{E}_{|\tau_f} \right] = -\frac{\gamma_x\gamma_y(\bar{y} - \hat{y})}{a_x\theta}$$

Specifically, for mutualistic and competitive species, a stock-based instrument,  $\tau_x$ , performs better since the gap between the size of sectors under both management regimes gets smaller. By contrast, for a prey-predator relationship, a sector-specific instrument is more effective.

## 4.2 Effort regulation

Now, let us assume that the social planner imposes a fee on the global effort level,  $\tau_w$ . Equation (2) thus becomes :  $p_x\lambda\theta x + p_y(1 - \lambda)\theta y = w + \tau_w$ . Combining this last equation with (3) and (8), we obtain the following expressions:

$$\hat{x}_{\tau_w} = \frac{(w + \tau_w)}{\theta p_x}, \quad \hat{y}_{\tau_w} = \frac{(w + \tau_w)}{\theta p_y}$$

Unlike the case of a sector or species-specific regulation, both stock levels are affected by the present scheme. More precisely, the stocks increase if a

tax is imposed, and decrease otherwise. This in turn impacts on the global effort level, the allocation share and the size of both sectors as follows:

$$\frac{\partial \hat{Z}_{\tau_w}}{\partial \tau_w} = \frac{\partial \hat{Z}_{\tau_w}}{\partial x} \cdot \frac{\partial \hat{x}_{\tau_w}}{\partial \tau_w} + \frac{\partial \hat{Z}_{\tau_w}}{\partial y} \cdot \frac{\partial \hat{y}_{\tau_w}}{\partial \tau_w}$$

with  $\hat{Z}_{\tau_w} = \left\{ \hat{E}_{\tau_w}; \hat{\lambda}_{\tau_w}; \hat{\lambda}_{\tau_w} \hat{E}_{\tau_w}; (1 - \hat{\lambda}_{\tau_w}) \hat{E}_{\tau_w} \right\}$ .

As previously, let us assume that the fee is a tax, and focus on the impact of changes in the two populations. Since we already computed the impact of species  $x$  (see equations (22) and (23)), we now focus on the impact of change in species  $y$ . We have:

$$\frac{\partial \hat{E}}{\partial y} = -\frac{(a_y - \gamma_x)}{\theta}; \quad \frac{\partial \hat{\lambda}}{\partial y} = \frac{(a_x a_y - \gamma_x \gamma_y)(\tilde{x} - \hat{x})}{(\theta E)^2} \quad (25)$$

$$\frac{\partial(\hat{\lambda} \hat{E})}{\partial y} = \frac{\gamma_x}{\theta}; \quad \frac{\partial((1 - \hat{\lambda}) \hat{E})}{\partial y} = -\frac{a_y}{\theta} \quad (26)$$

Combining these equations with equations (22) and (23) and the impact of the tax on the stock, we can assess the impact of this tax on the different variables characterizing the behavior of fishermen.

$$\frac{\partial(\hat{E})}{\partial \tau_w} = \frac{p_x(\gamma_x - a_y) + p_y(\gamma_y - a_x)}{\theta^2 p_x p_y} \quad (27)$$

$$\frac{\partial(\hat{\lambda})}{\partial \tau_w} = \frac{(a_x a_y - \gamma_x \gamma_y)[p_x(\tilde{x} - \hat{x}) - p_y(\tilde{y} - \hat{y})]}{\theta^3 E^2 p_x p_y} \quad (28)$$

$$\frac{\partial(\hat{\lambda} \hat{E})}{\partial \tau_w} = \frac{\gamma_x p_x - a_x p_y}{\theta^2 p_x p_y}; \quad \frac{\partial((1 - \hat{\lambda}) \hat{E})}{\partial \tau_w} = \frac{\gamma_y p_y - a_y p_x}{\theta^2 p_x p_y} \quad (29)$$

The impact of such mechanism is more ambiguous than that of the two specific taxes, since it depends on combined effects resulting from the economic variables and the biological parameters. We notice that its effect on the allocation rate does not depend on biological interaction between species, but only on the difference between the value (for each species) of the extra population density if it is not harvested. Moreover, the size of the fleet and the pressure on both sectors will *always* decrease when species are competitive. Finally and perhaps more interestingly, we identify conditions under which a fleet-based tax alleviates the pressure on either both species or on only one. This is the aim of the next proposition.<sup>7</sup>

<sup>7</sup>Again the fee is assumed to be positive.

**Proposition 8** *A fleet-based regulation scheme enables to either (i) reduce the size of both sectors; (ii) reduce the size of the  $x$ -species sector and increase that of the other sector if  $\gamma_y > 0$  and  $\frac{p_y}{p_x} > \frac{a_y}{\gamma_y}$ ; or (iii) decrease the size of the  $y$ -species sector and increase that of the other sector if  $\gamma_x > 0$  and  $\frac{p_y}{p_x} < \frac{\gamma_x}{a_x}$ .*

Proposition 8 highlights that changes in harvesting pressure will depend on the relative value of a species, and on the nature and intensities of inter and intra-species relationships. Specifically, we observe that the pressure is more likely to increase on species with a high relative price ( $p_i/p_j$  large) and to decrease on the species that is highly important within the ecological relationship ( $\frac{a_i}{\gamma_i}$  small). Table 3 summarizes the impact of an effort-based tax instrument.

Table 3: Impact of effort-based tax

	Predation	Competition	Mutualism
Share	+/-	+/-	+/-
Total Effort	+/-	-	+/-
Fishery activity for $x$	-	-	+/-
Fishery activity for $y$	+/-	-	+/-

We now proceed with the characterization of the second-best optimal effort-based scheme (implementing the first best effort level).

**Proposition 9** *If a fishery manager imposes an effort fee, the second-best scheme is characterized by:*

$$\tau_w^* = \frac{p_x p_y \theta [(\bar{x} - \hat{x})(\gamma_x - a_x) + (\bar{y} - \hat{y})(\gamma_y - a_y)]}{p_x(\gamma_y - a_y) + p_y(\gamma_x - a_x)}$$

*Thus, it is optimal to tax effort when species are competitive. For other types of relationship, a tax is not always second-best. It is optimal to subsidize effort if and only if the following conditions hold:*

$$\frac{p_y}{p_x} > \frac{\gamma_y - a_y}{a_x - \gamma_x} > \frac{\bar{x} - \hat{x}}{\bar{y} - \hat{y}} > 0. \quad (30)$$

This result yields interesting insights, as it shows whether one should tax or subsidize effort (via a license fee for instance) according to the type of biological interactions. First, since  $\bar{x} > \hat{x}$  and  $\bar{y} > \hat{y}$ ,  $\tau_w^*$  will be positive for competitive relationships. Second, the conclusion is ambiguous for other relationships. While the rate will be positive for cases where  $\gamma_y \leq a_y$  and  $\gamma_x \leq$

$a_x$  (the intensity of the inter-species relationship is weaker than intra-species competition), some qualification is needed when one or the other inequality does not hold. Provided that the intensity of the inter-species relationship is stronger than intra-species competition for one species, implementing the socially optimal effort level will require subsidization as long as the price ratio  $\frac{p_y}{p_x}$  will be sufficiently high.<sup>8</sup>

Let us conclude the section with the assessment of the efficiency of this instrument by comparing the size of the sectors under regulation to that under sole ownership:

$$\begin{aligned}\bar{\lambda}\bar{E} - \hat{\lambda}_{\tau_w}\hat{E}_{\tau_w} &= \frac{a_x(\hat{x}_{\tau_w} - \bar{x}) + \gamma_x(\bar{y} - \hat{y}_{\tau_w})}{\theta} \\ (1 - \bar{\lambda})\bar{E} - (1 - \hat{\lambda}_{\tau_w})\hat{E}_{\tau_w} &= -\left(\bar{\lambda}\bar{E} - \hat{\lambda}_{\tau_w}\hat{E}_{\tau_w}\right)\end{aligned}$$

The comparison is much more complicated than the one with a sector/species-specific tax since both population stocks are affected, and the comparison between stocks is ambiguous. However, we notice that if one sector is larger than the socially optimal level, then the other sector will be smaller.

If we want to assess which instrument performs better, we can focus on the sector harvesting the  $x$ -species.<sup>9</sup> It is then easy to claim that the sector-based regulation is the most efficient one since the regulated sector reaches its optimal size. Finally, comparing the species-specific tax with the effort-based tax, we get:

$$\left[\bar{\lambda}\bar{E} - \hat{\lambda}_{\tau_w}\hat{E}_{\tau_w}\right] - \left[\bar{\lambda}\bar{E} - \hat{\lambda}_{\tau_x}\hat{E}_{\tau_x}\right] = \frac{a_x(\hat{x}_{\tau_w} - \bar{x}) + \gamma_x(\hat{y} - \hat{y}_{\tau_w})}{\theta}$$

The sign is still ambiguous. Nevertheless, if we consider cases where (for instance) we have  $\bar{x} > \hat{x}_{\tau_w}$  and  $\hat{y}_{\tau_w} > \bar{y}$ ,<sup>10</sup> then the effort-based regulation performs better than the species-specific regulation for mutualistic species. Indeed, the gap with respect to the socially optimal situation is smaller. Once again, when first-best management is not possible, the choice of which second-best policy to implement depends on the specifics of the situation.

<sup>8</sup>We provide conditions under which  $\tau_w^*$  takes on negative values in the appendix.

<sup>9</sup>Please note that the discussion focuses on the case of the  $x$ -species sector. It is useful to keep in mind that, as said at the beginning of the analysis, an effort-based regulation has a joint effect on the stocks of both species.

<sup>10</sup>The cases described do exist. For instance, if  $a_i > \gamma_i$ , then it is easily checked that  $\bar{x} - \hat{x}_{\tau_w}$  and  $\bar{y} - \hat{y}_{\tau_w}$  have opposite signs.

## 5 Conclusion

We analyze second-best management systems for multispecies fisheries. We focus on emerging issues when a species (a sector) is left unregulated, or when only the global effort level (not its allocation) can be controlled. Using a model of targeted fishing enables us to assess whether effort will be redirected from regulated to unregulated species, and how this redirection is affected by the nature of the biological interaction. It significantly differs under competitive or mutualistic relationships, or depending on whether the regulated species is a prey or a predator. Among other counter-intuitive results, we show that an effort-based management system (while it does not target a given species) will induce a reallocation of effort to the predator species, but will release the pressure on competitive ones. Finally, we characterize and contrast optimal (second-best) regulatory schemes under the different types of management. Depending on the biological interaction, it consists in a tax or a subsidy. We highlight how the characterization depends on the management system. We evaluate the performance of second-best optimal schemes (with respect to the socially optimal outcome) and finally assess which is most appropriate (in that it gets closer to the first best outcome).

All these results provide insights on the implications of incomplete regulation schemes (which is a feature of most existing systems) as they show how one should expect a change in the pressure on unregulated species, and how this qualitatively depends on the nature of the biological interactions. In the present paper we focused on open access regimes, and it would be interesting to extend the analysis to the case of common property settings, where strategic interactions may exist between resource users. This is left for future research.

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# Appendix

## Proof of Proposition 1

As usual, focusing on the local stability of the dynamic system (2), (3) and (4) we can derive the following Jacobian matrix :

$$J = \begin{pmatrix} -a_x x^* & \gamma_x x^* & -\Theta \lambda x^* \\ \gamma_y y^* & -a_y y^* & -\Theta(1-\lambda)y^* \\ p_x \Theta \lambda E^* & p_y \Theta(1-\lambda)E^* & 0 \end{pmatrix}$$

Following Wirl [36], we know that it is sufficient to have  $tr(J) < 0$  and  $\det(J) < 0$  for the equilibrium to be a saddle point. We easily observe that  $tr(J) = -a_x x^* - a_y y^* < 0$ .

It remains to check the sign of the determinant :

$$\det(J) = -\Theta^2 E^* x^* y^* [(1-\lambda)p_y (a_x(1-\lambda) + \gamma_y \lambda) + \lambda p_x (\gamma_x(1-\lambda) + a_y \lambda)].$$

If species are mutualistically-dependent, then  $\det(J) < 0$ . If species are in competition, it is sufficient that  $-\frac{a_x}{\gamma_y} \geq \frac{\lambda}{1-\lambda} \geq -\frac{\gamma_x}{a_y}$ , which is possible under condition (5), to ensure that  $\det(J) < 0$ . For prey-predator relationship with  $x$  the prey, then it is sufficient that  $\frac{\lambda}{1-\lambda} \geq -\frac{\gamma_x}{a_y}$  to ensure  $\det(J) < 0$ .

## Proof of Proposition 2

From conditions (13) and (14), we obtain  $\mu_x^{os} = \frac{p_x \theta \bar{x} - w}{\theta \bar{x}}$  and  $\mu_y^{os} = \frac{p_y \theta \bar{y} - w}{\theta \bar{y}}$ . Then, using conditions (3) and (4), we find that

$$\bar{E} = \frac{\bar{x}(s\beta - a) - \xi + \alpha - s\bar{y}}{\theta} ; \bar{\lambda} = \frac{\alpha - a\bar{x} - s\bar{y}}{\bar{x}(s\beta - a) - \xi + \alpha - s\bar{y}}$$

Finally, setting  $\dot{x} = \dot{y} = 0$  (and using expressions (3) and (4)) enables to obtain the implicit expressions of  $\bar{x}$  and  $\bar{y}$  as functions of  $\bar{E}$  and  $\bar{\lambda}$ .

## Proof of Proposition 3

According to Dockner [13], we know if we have the trace of the jacobian matrix  $Tr(J) > 0$ , the sum of the principal minors  $\Omega < 0$  and the determinant  $\det(J) > 0$ , we have the sufficient conditions to observe saddle point stability properties.

$$J = \begin{pmatrix} \frac{\partial \dot{x}}{\partial x} & \frac{\partial \dot{x}}{\partial y} & \frac{\partial \dot{x}}{\partial \mu_x} & \frac{\partial \dot{x}}{\partial \mu_y} \\ \frac{\partial \dot{y}}{\partial x} & \frac{\partial \dot{y}}{\partial y} & \frac{\partial \dot{y}}{\partial \mu_x} & \frac{\partial \dot{y}}{\partial \mu_y} \\ \frac{\partial \dot{\mu}_x}{\partial x} & \frac{\partial \dot{\mu}_x}{\partial y} & \frac{\partial \dot{\mu}_x}{\partial \mu_x} & \frac{\partial \dot{\mu}_x}{\partial \mu_y} \\ \frac{\partial \dot{\mu}_y}{\partial x} & \frac{\partial \dot{\mu}_y}{\partial y} & \frac{\partial \dot{\mu}_y}{\partial \mu_x} & \frac{\partial \dot{\mu}_y}{\partial \mu_y} \end{pmatrix} \Big|_{(x^*, y^*, \mu_x^*, \mu_y^*)}$$

The principal minors

$$\Omega = \left| \begin{array}{cc} \frac{\partial \dot{x}}{\partial x} & \frac{\partial \dot{x}}{\partial \mu_x} \\ \frac{\partial \dot{\mu}_x}{\partial x} & \frac{\partial \dot{\mu}_x}{\partial \mu_x} \end{array} \right| + \left| \begin{array}{cc} \frac{\partial \dot{y}}{\partial y} & \frac{\partial \dot{y}}{\partial \mu_y} \\ \frac{\partial \dot{\mu}_y}{\partial y} & \frac{\partial \dot{\mu}_y}{\partial \mu_y} \end{array} \right| + 2 \left| \begin{array}{cc} \frac{\partial \dot{x}}{\partial y} & \frac{\partial \dot{x}}{\partial \mu_y} \\ \frac{\partial \dot{\mu}_x}{\partial y} & \frac{\partial \dot{\mu}_x}{\partial \mu_y} \end{array} \right|$$

We notice that

$$\begin{aligned} Tr(J) &= 2\delta > 0 ; \quad \Omega = -a_x x^*(\delta + a_x x^*) - a_y y^*(\delta + a_y y^*) - 2x^* y^* \gamma_x \gamma_y < 0 \\ \det(J) &= x^* y^* (a_x a_y - \gamma_x \gamma_y) [(\delta + a_x x^*)(\delta + a_y y^*) - \gamma_x \gamma_y x^* y^*] > 0 \end{aligned}$$

with  $a_x a_y > \gamma_x \gamma_y$ . Therefore, there needs no condition for the competitive and mutualistic relationship. However, this requires that  $a_x x^*(\delta + a_x x^*) + a_y y^*(\delta + a_y y^*) > -2x^* y^* \gamma_x \gamma_y$  for predation.

## Proof of Proposition 4

The cases of competitive and of predator-prey relationships are straightforward. Since  $\gamma_x$  and  $\gamma_y$  are negative in the case of competitive species, conditions (20) and (21) enable to conclude the proof. Now, in the case of a predator-prey relationship, the prey-fishery sector is easily checked to be always larger under open access. However, the following condition ( $y$  denoting the predator species) ensures that the predator-fishery sector will be larger under socially optimal management:

$$(1 - \bar{\lambda})\bar{E} > (1 - \hat{\lambda})\hat{E} \Leftrightarrow \frac{\bar{y} - \hat{y}}{\bar{x} - \hat{x}} > \frac{\gamma_y}{a_y}$$

Regarding mutualistic relationships, let us analyze conditions to observe a larger pressure under socially optimal management. From conditions (20) and (21), we obtain

$$\begin{aligned} \bar{\lambda}\bar{E} > \hat{\lambda}\hat{E} &\Leftrightarrow \frac{\bar{y} - \hat{y}}{\bar{x} - \hat{x}} > \frac{a_x}{\gamma_x} \\ (1 - \bar{\lambda})\bar{E} > (1 - \hat{\lambda})\hat{E} &\Leftrightarrow \frac{\gamma_y}{a_y} > \frac{\bar{y} - \hat{y}}{\bar{x} - \hat{x}} \end{aligned}$$

This implies that  $\frac{\gamma_y}{a_y} > \frac{a_x}{\gamma_x} \Leftrightarrow \gamma_x \gamma_y - a_x a_y > 0$ , which contradicts condition (5). Therefore, conditions (20) and (21) cannot be simultaneously positive. Specifically, if one has  $\frac{\bar{y} - \hat{y}}{\bar{x} - \hat{x}} > \max \left\{ \frac{a_x}{\gamma_x} \right\}$  then the  $x$ -species sector is larger under socially optimal management. If one has  $\min \left\{ \frac{a_x}{\gamma_x} \right\} > \frac{\bar{y} - \hat{y}}{\bar{x} - \hat{x}}$  then we obtain the same conclusion for species  $y$ . Under condition (5) we deduce that  $\max \left\{ \frac{a_x}{\gamma_x} \right\} = \frac{a_x}{\gamma_x}$  and  $\min \left\{ \frac{a_x}{\gamma_x} \right\} = \frac{\gamma_y}{a_y}$ , which concludes the proof.

## Proof of Proposition 6

Since the optimal stock level is higher than the stock observed under open access,  $\bar{x} > \hat{x}$  and  $\bar{y} > \hat{y}$ , the sign of  $\tau_f$  depends on the interactive term,  $\gamma_x$ . When  $\gamma_x$  is negative,  $\tau_f$  is positive. When  $\gamma_x$  is positive, the sign of  $\tau_f$  could be positive or negative.

## Proof of Proposition 7

Using equations (20) and (21), we check whether the difference between the open access and socially optimal outcomes is larger than that between the regulated open access and

socially optimal outcomes.

$$\begin{aligned}
(\bar{\lambda}\bar{E} - \hat{\lambda}\hat{E}) - (\bar{\lambda}\bar{E} - \hat{\lambda}_{\tau_x}\hat{E}_{\tau_x}) &= -\frac{a_x(\bar{x} - \hat{x})}{\theta} < 0 \\
(\bar{\lambda}\bar{E} - \hat{\lambda}\hat{E}) - (\bar{\lambda}\bar{E} - \hat{\lambda}_{\tau_f}\hat{E}_{\tau_f}) &= \bar{\lambda}\bar{E} - \hat{\lambda}\hat{E} \\
[(1 - \bar{\lambda})\bar{E} - (1 - \hat{\lambda})\hat{E}] - [(1 - \bar{\lambda})\bar{E} - (1 - \hat{\lambda}_{\tau_x})\hat{E}_{\tau_x}] &= \frac{\gamma_y(\bar{x} - \hat{x})}{\theta} \\
[(1 - \bar{\lambda})\bar{E} - (1 - \hat{\lambda})\hat{E}] - [(1 - \bar{\lambda})\bar{E} - (1 - \hat{\lambda}_{\tau_f})\hat{E}_{\tau_f}] &= \frac{a_x\gamma_y(\bar{x} - \hat{x}) + \gamma_x\gamma_y(\bar{y} - \hat{y})}{a_x\theta}
\end{aligned}$$

## Proof of Proposition 8

The proof will follow from inspection of conditions (29). Under condition (5), we notice that both conditions can be negative. Moreover condition (5) implies that  $\frac{a_x}{\gamma_x} \geq \frac{a_y}{\gamma_y}$ , we thus obtain (in the case of mutualistic species) that inequality  $\frac{p_y}{p_x} > \frac{a_y}{\gamma_y}$  implies that the size of the x-species (respectively, y-species) sector decreases (respectively, increases). Inequality  $\frac{p_y}{p_x} < \frac{\gamma_x}{a_x}$  implies that the size of the x-species (respectively, y-species) sector increases (respectively, decreases).

## Proof of Proposition 9

The proof is straightforward by simple inspection of the expression of  $\tau_w^*$ : conditions (30) are necessary and sufficient to ensure that  $\tau_w^*$  has a negative value (keeping in mind that  $a_x a_y - \gamma_x \gamma_y \geq 0$  implies that  $a_x \geq \gamma_x$  in the cases described in the proposition).

## Cases where $\tau_w^*$ takes on negative values

It can be checked that, depending on the specific economic returns, the conditions ensuring the use of subsidization are non degenerate. For instance, if  $w$  gets arbitrarily close to zero, then  $\hat{x}$  and  $\hat{y}$  will get arbitrarily close to zero as well. Moreover, the socially optimal stock levels get arbitrarily close to:

$$\bar{x} = \frac{p_y(\delta - \alpha_y)[p_x\gamma_x + p_y\gamma_y] + 2a_y p_x p_y(\delta - \alpha_x)}{(p_x\gamma_x + p_y\gamma_y)^2 - 4a_x a_y p_x p_y}, \quad \bar{y} = \frac{\bar{x}(p_x\gamma_x + p_y\gamma_y) - p_y(\delta - \alpha_y)}{2a_y p_y}.$$

The ratio  $\frac{\bar{x} - \hat{x}}{\bar{y} - \hat{y}}$  gets arbitrarily close to

$$\frac{\bar{x}}{\bar{y}} = \frac{p_y(\delta - \alpha_y)[p_x\gamma_x + p_y\gamma_y] + 2a_y p_x p_y(\delta - \alpha_x)}{2a_x p_x p_y(\delta - \alpha_y) + p_x(\delta - \alpha_x)[p_x\gamma_x + p_y\gamma_y]}.$$

Then inequality  $\frac{p_y}{p_x} > \frac{\bar{x}}{\bar{y}}$  is equivalent to:

$$p_x p_y \{(\alpha_y - \alpha_x)(p_x\gamma_x + p_y\gamma_y) - 2a_x p_y(\delta - \alpha_y) + 2a_y p_x(\delta - \alpha_x)\} > 0.$$

If the price of species  $x$  becomes arbitrarily small then the above inequality becomes:

$$(\alpha_y - \alpha_x)\gamma_y > 2a_x(\delta - \alpha_y) \Leftrightarrow \frac{\alpha_y - \alpha_x}{\delta - \alpha_y} > \frac{2a_x}{\gamma_y}.$$

Thus, cases where  $w$  and  $p_x$  have small enough (and appropriate) values correspond to situations where  $\tau_w^*$  can take on negative values.