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**Multi-jurisdiction quota enforcement
for transboundary renewable resources**

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Abstract

Many renewable resources, such as fish stocks, water or environmental quality, are shared between different countries. The management of such resources then relies on international agreements. We develop a model of a shared renewable resource for which there is an international agreement that determines each country's share of total extractions. Each government is responsible for the enforcement of their national quota. The countries can cheat on the agreement by reducing enforcement efforts and thereby inducing their firms to violate their quotas. We analyze the effects of this in a differential game framework. There are two games. First, a Stackelberg game between the government and the firms within each country. Second, an enforcement game at the international level between different governments. Our results suggest that no free-riding only occurs if countries have asymmetric beliefs regarding the environmental preferences of rival countries. The extent of free-riding in enforcement can be influenced by both domestic and international policy instruments. The effectiveness of domestic instruments (legislation) versus international instruments (treaties) depends to a large extent on resource dynamics and the countries' preferences for sustainability.

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1   Introduction

The management of common pool resources (CPRs) such as the global environment, fish stocks or water, has received much attention in the economic literature. The main challenge lies in the common pool property of the resource; an individual who uses the resource obtains the full benefit associated with this, while the reduction in the stock of the resource affects everyone. Much of the existing work deals with how this externality can be internalized to force individuals to take into account the full cost of using the resource. Many CPRs are transboundary or shared between several countries. The global environment serves as a good example. As a country emits greenhouse gases (GHGs) into the atmosphere, the concentration of GHGs in the atmosphere increases, which may affect the future environment of all countries. Much of the existing work focuses on whether and how cooperative management can be achieved, and on the stability of agreements and coalitions.

The major environmental challenges today are of a global rather than a local nature. Game theoretical analysis of international environmental problems, particularly CO2 emissions and global warming, has received increasing attention (see Finus & Nr, 2008). Another example are fisheries, where about one-third of all harvested fish worldwide is from shared or transboundary fish stocks (Munro, 2008). Following the establishment of the 200 nautical mile exclusive economic zones (EEZs) in 1982, there has been an increasing focus on the management of transboundary fish stocks. According to the United Nation's Convention on the Law of the Sea of 1982, countries sharing a fish stock must negotiate a cooperative management agreement for the stock, but they are not required to actually come to an agreement. This has been the focus of much of the existing game-theoretical work on shared fish stocks, i.e., whether and how countries can reach a cooperative solution (see the reviews by Sumaila, 1999; Munro, 2008). Non-cooperative game theoretic models have also been surveyed (see the reviews by Kaitala, 1986; Kaitala & Lindroos, 2007).

The focus of our study differs from the existing game theoretical work in that we go one step further by asking what happens once a sharing agreement has been established. Does each country in fact impose the conditions of the sharing agreement on their industries by ensuring strict enough enforcement of quotas or standards to meet international obligations? Let us use the fishery as an illustrative example. In most, if not all commercial fisheries, illegal fishing is a serious and significant problem (Agnew et al., 2009). Hence, even if the countries have come to an agreement about the sharing of the total quota and have set the national quotas accordingly, it is not necessarily the case that the countries can or wish to enforce these national quotas. In absence

of enforcement, the fishing firms have incentives to exceed their quotas to increase profits as long as the fishery is profitable. Furthermore, it is well-known from the enforcement literature that the compliance level depends on the level of enforcement. Thus, even if a country accepts a sharing agreement and imposes its national quota on the fishing fleet, the total catches of the fleet may exceed the national quota due to non-compliance. We may in fact end up in a situation where the national governments deliberately operate at low levels of enforcement in order to get a higher share of total catches than specified by the sharing agreement. The same story can be told about national GHG emissions and the global environment, and other shared CPRs.

In this paper we develop a model of a CPR that is shared between two countries. There is a sharing agreement in place that specifies each country's share of the total quota, which is determined by an independent third party. The two countries' governments are responsible for the enforcement of their national quotas, which means that each country must decide on its level of enforcement aimed at reducing illegal extraction by its CPR industry. National governments therefore play a game against their resource industries, where the government is the Stackelberg leader and the industry is a Stackelberg follower. Furthermore, the two governments play a game against each other where they compete for shares of total extraction by varying enforcement effort, a game in which they exhibit Nash behavior.

Our paper draws on the enforcement literature and the game theoretical literature. The enforcement part of our model is based on the basic fisheries enforcement model (Sutinen & Andersen, 1985). Of related game theoretical work, Sandal & Steinshamn (2004) study competitive harvesting from a common pool resource as a dynamic Cournot game. They focus on the situation where players are perfectly myopic, which reduces the problem to solving a static game in each period. In our analysis we assume that the governments solve dynamic optimization problems to maximize the current value of their share of the resource net of enforcement costs. Other related work includes (Benchekroun & van Long, 2002) who study a transboundary fishery in which the resource migrates along the coastline within the framework of a differential game. Our model assumes both nations move simultaneously and that neither has a first-mover advantage. It therefore differs from the approach of Benchekroun & van Long. The integration of enforcement into the game-theoretic model of shared resources is relatively new and few other papers attempt to do this. An exception is Xepapadeas (2005) who analyzes a compliance game for commons pool resources using evolutionary game theory. However, to our knowledge the study of compliance using differential game theory is a novel contribution to this literature.

The main contribution of the paper is to offer new insights into the management of

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transboundary CPRs. An increasingly relevant example is pollution and global warming. If countries agree on restricting total emissions of greenhouse gases, such as under the Kyoto protocol, the actual effect of the treaty will depend on the individual countries' willingness and ability to enforce the emission targets. The distinction between the international burden sharing agreement on the one hand, and national compliance and enforcement on the other, offers new understanding of international environmental management. The results obtained in the paper are equally relevant for other industries in which international agreements are imposed on national industries that restrict firms' behavior.

The paper is organized as follows. We start out by developing the general model in section 2. We then analyse the socially optimal level of enforcement effort in section 3.1, before analyzing each nations inter-temporal effort determination problem in a strategic setting in section 3.2. This defines a differential game between two nations in determining effort. In sections 3.3, the results of the differential game are compared to the socially optimal level and the determinants of free-riding are studied. In section 4, we analyze the impact on industry profits of varying the total quota. The last section concludes.

2   Model

We develop a model of a transboundary resource that is shared between two countries. A sharing agreement has been established that states that the total quota should be set according to recommendations from an (independent) international agency and that each country is entitled to a given share of the total quota. To ensure that the model is tractable, we eliminate the possibility for strategic behavior at this level by assuming that this recommendation cannot be affected or rejected by the governments sharing the resource. Furthermore, we let the total quota be determined as a fixed proportion of the resource stock so that $Q = \theta X$, where Q is the total quota, X is the total resource stock and $\theta \in (0, 1)$ is a constant. The sharing agreement entitles country i to a share γ_i of the total quota ($i = 1, 2$). The two countries' shares must sum to one: $\gamma_1 + \gamma_2 = 1$.

The governments are responsible for enforcement of the national quotas. Enforcement is costly and we let the enforcement cost be a linear function of enforcement effort, e: $C(e) = c_e e$. The inspection probability is a function of the enforcement level. To keep things simple we assume that there is a one-to-one relationship between en-

forcement effort and the inspection probability. Thus, $e \in [0, 1]$ can be interpreted as the inspection probability.

The individual firms in the resource industry seek to maximize expected profits. Each of the two national industries is regulated by non-transferable quotas that are allocated to firms. Hence, each firm is entitled to a fixed share of the national quota. We assume that all firms are identical and focus the analysis on the representative firm of each industry. The number of firms in each industry is large enough for the marginal stock effect of individual resource use to be negligible. With a constant share of the quota, the problem of the firm is to determine the production level that maximizes expected profits at each instant of time, given the quota. Hence, the optimization problem of the firm is static.

The payoff of the representative firm consists of two parts; the operating result and possibly a fine payment if the firm's quota is exceeded and the quota violation is detected. If the firm is inspected and found to have exceeded its quota, a fine must be paid. The total fine payment F depends on how much the firm's total production exceeded the quota. With the fine per unit denoted by f, the total fine payment can be expressed as:

$$F_i = f_i \left(q_i - \gamma_i \theta X \right), \tag{1}$$

where q_i denotes the extraction of the representative firm in country i. Assuming that we are dealing with a profitable industry and knowing that non-compliance is an option for the firms, it is clear that the national industries will produce at least as much as their quotas entitle them to: $q_1 + q_2 \geq Q$. Consequently, the expected (or average) fine payment is non-negative.

Given that the probability of being inspected is e then with all firms producing at least at quota levels, the probability of paying the fine F_i is e. The operating profits are independent of whether the firm is inspected and fined. We can then express the expected profits of the representative firm in country i as follows:

$$\pi_i = pq_i - \frac{c_i}{2} q_i^2 - e_i f_i \left(q_i - \gamma_i \theta X \right), \tag{2}$$

where p is a constant unit price and c_i is a cost parameter. Solving the profit maximization problem of the firm (equation 2) yields the firm's optimal production level

$$q_i^* \left(e_i \right) = \frac{p - e_i f_i}{c_i}, \tag{3}$$

where $i = 1, 2$. The higher the enforcement effort, the lower the produced quantity q_i. Equation (3) is the reaction function of the firm in the Stackelberg game between

the government and the firm, as it gives the relationship between the firm's production level and the government's level of enforcement. Notice that the production level of the firm is independent of the firm's share of the quota. This is a result of the assumption that we are dealing with a profitable resource industry in which all firms will produce at least at quota levels. With the fine structure as assumed above, i.e., with a constant marginal fine, the firm's production level becomes independent of the size of the quota. However, the firm only produces if production according to the reaction function (3) yields non-negative profit, and this requirement depends on the quota γ.

With this in place, we turn to the problem of the governments. Each government seeks to maximize discounted expected industry profit net of enforcement costs by choosing the level of enforcement e. Each government values a viable stock and therefore has a preference for the total quota not to be exceeded. The problem of government i can be expressed as follows:

$$\max_{e_i} \int_0^\infty e^{-rt} \left\{ pq_i^*(e_i) - \frac{c_i^*}{2} q_i(e_i)^2 - w_i \left(q_i^*(e_i) + q_j^*(e_j) - \theta X \right) - c_e e_i \right\} dt, \tag{4}$$
$$\text{s.t. } \dot{X} = aX - q_1^*(e_1) - q_2^*(e_2)$$

where $i = 1, 2, i \neq j$. The first term in the objective function is the representative firm's profit, which the government would like to see maximized. However, they do not want this to occur at the cost of violating the international quota, and therefore, the second term is the welfare loss of exceeding the total quota. Hence, the governments care not only about violations of their own industry's quota, but whether the total quota is being met, which ensures that the resource remains viable.[1] Consider as an example international treaties for reducing global carbon emissions. A country may have incentives to increase own emissions, but is still interested in the global emission target to be reached. The parameter w is a welfare weight associated with the government's preference for the total quota to be met. The larger the value of w, the stronger is the preference for meeting the quota. We will refer to this as the country's preference for sustainability. The third term is the cost of enforcement.

3 Analysis

Having presented the basics of the model, we can now solve the dynamic resource problem under different assumptions about the game. We start out by solving the joint enforcement case, which is equivalent to having a social planner who is responsible for

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[1]A similar assumption is made in the so-called lake game, where pollution reduces the welfare derived from the lake (Dechert & Brock, 2000).

enforcement in both countries. Next, we turn to the case where the countries compete in an enforcement game.

3.1   Joint enforcement: Social planner

We start out by considering the case where a social planner chooses the enforcement effort for each of the two countries that maximizes aggregate discounted industry profits net of enforcement costs and welfare losses associated with the aggregate quota being exceeded. This will provide a benchmark for the dynamic game. The dynamic problem of the social planner can be stated as:

$$
\begin{aligned}
\max_{e} \int_0^\infty e^{-rt} & \left\{ p\left(q_1(e_1) + q_2(e_2)\right) - \tfrac{c_1}{2} q_1(e_1)^2 - \tfrac{c_2}{2} q_2(e_2)^2 \right. \\
& \left. - (w_1 + w_2)\left[q_1(e_1) + q_2(e_2) - \theta X\right] - c_e\left(e_1 + e_2\right) \right\} dt, \\
\text{s.t. } & \dot{X} = aX - q_1(e_1) - q_2(e_2),
\end{aligned}
\tag{5}
$$

where the reaction function of industry i, $q_i(e_i)$ $(i = 1, 2)$, is given by equation (3).

The first order conditions of the problem are:

$$
\frac{\partial \tilde{H}}{\partial e_i} = p\frac{\partial q_i}{\partial e_i} - c_i q_i \frac{\partial q_i}{\partial e_i} - (w_1 + w_2)\frac{\partial q_i}{\partial e_i} - c_e - \lambda \frac{\partial q_i}{\partial e_i} = 0, i = 1, 2
\tag{6}
$$

$$
\dot{\lambda} - r\lambda = -\frac{\partial \tilde{H}}{\partial X} = -\lambda a - (w_1 + w_2)\theta,
\tag{7}
$$

where $\tilde{H}$ denotes the Hamiltonian of the optimization problem in (5). By rearranging the first equation (6) we obtain the optimal enforcement level as a function of the shadow price of the stock, $\lambda(t)$:[2]

$$
e_i^{**} = \frac{1}{f_i}\left[w_1 + w_2 + \lambda - \frac{c_e c_i}{f_i}\right].
\tag{8}
$$

It can be shown that $\lambda(t)$ is constant and equal to $\lambda = \frac{\theta(w_1 + w_2)}{r - a}$ (see appendix). Consequently, the optimal enforcement level is constant over time. Substituting in for λ in equation (8) and rearranging yields the optimal enforcement level in closed-form:

$$
e_i^{**} = \frac{1}{f_i}\left[(w_1 + w_2)\left(1 + \frac{\theta}{r - a}\right) - \frac{c_e c_i}{f_i}\right].
\tag{9}
$$

As one would expect, the enforcement level is the same in both countries under joint enforcement if the countries are identical. This is the case even if the countries value

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[2]Throughout the paper, superscript ** indicates that we are referring to the social planner case.

sustainability differently $(w_1 \neq w_2)$. This means that if one country places a very low value on the total quota not being exceeded relative to the other country, it still has to contribute to the enforcement of the quota at the same level as the other country. This emphasizes one of the issues facing those trying to reach a cooperative solution over the sharing of CPRs. If, however, the countries differ only in terms of extraction costs c_i, equation (9) shows that this requires a higher level of enforcement in the country with the lower production cost. This is because all else equal, the incentives of an industry to exceed quotas increase the higher the efficiency of this industry.

The optimal enforcement level is increasing in the countries' preferences for sustainability (w_i), given that the growth rate of the resource is below the discount rate $(r > a)$. In the following, we restrict our analysis to this case.[3]

By substituting for optimal enforcement e^{**} into the reaction function of the representative firm (3), we find the optimal extraction level under joint management:

$$q_i^{**} = \frac{1}{c_i} \left[p - (w_1 + w_2) \left(1 + \frac{\theta}{r-a} \right) + \frac{c_e c_i}{f_i} \right]. \tag{10}$$

Finally, the steady-state stock level is given by $X^{**} = \frac{1}{a} [q_1^{**} + q_2^{**}]$, and by substituting in for optimal extraction levels and rearranging, we obtain:

$$X^{**} = \frac{1}{a} \left\{ \left(\frac{1}{c_1} + \frac{1}{c_2} \right) \left[p - (w_1 + w_2) \left(1 + \frac{\theta}{r-a} \right) \right] + c_e \left(\frac{1}{f_1} + \frac{1}{f_2} \right) \right\}. \tag{11}$$

The derivation of the optimal stock level is shown in the appendix.

The steady-state stock level is increasing in the cost of enforcement c_e and decreasing in the magnitude of the fines f_i, but at a declining rate. An increase in enforcement costs reduces the level of enforcement, which increases extraction and therefore the stock level in steady state since this requires $X = \frac{1}{a} [q_1 + q_2]$. The marginal effects are summarized in table 1.

3.2 Dynamic game

Let us now return to the original problem, in which the two countries play an enforcement game against each other. The optimization problems of the governments

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[3]This may immediately seem like a restrictive assumption to those familiar with natural resource models. However, when using a linear growth function, the growth rate a is not comparable with the intrinsic growth rate of the logistic growth function. Keep in mind that the intrinsic growth rate is the proportional growth rate of the resource as the resource stock approaches zero. At higher stock levels, the proportional growth rate of the logistic growth function is lower than the intrinsic growth rate. Hence, the assumption that $r > a$ is not as restrictive as it may seem if one compares with the intrinsic growth rate from the logistic growth function.

(equation 4) define an infinite horizon differential game between the two countries. A key assumption is that each country knows the reaction function of the resource industries in both countries (cf. equation 3). However, a country may only know its own industry's reaction function, while it may take the behavior of the industry of the other country as fixed (Nash behavior).

Inserting the industries' reaction functions into the setup of the differential game produces a linear quadratic differential game in e_i, which can be solved using the Riccati method. This results in the following pair of Hamilton-Jacobi-Bellman (HJB) equations:

$$
rV^i(X) = \max \left\{ p \frac{p - e_i f_i}{c_i} - \frac{c_i}{2} \left(\frac{p - e_i f_i}{c_i} \right)^2 - w_i \left(\frac{p - e_i f_i}{c_i} + \frac{p - e_j(X,t) f_j}{c_j} - \theta X \right) - c_e e_i \right.
$$
$$
\left. + V_X^i \left[aX - \frac{p - e_i f_i}{c_i} - \frac{p - e_j(X,t) f_j}{c_j} \right] \right\},
$$
(12)

where $i = 1, 2, i \neq j$. $V^i(X)$ and V_X^i denote the value function of country i and its partial derivative with respect to the resource stock X, respectively. The function $e_j(X, t)$ refers to the feedback strategy of the other player, which is taken as given in a Nash equilibrium. The first-order conditions are:

$$
- \frac{p f_i}{c_i} - c_i \left(\frac{p - e_i f_i}{c_i} \right) \left(-\frac{f_i}{c_i} \right) + \frac{w_i f_i}{c_i} - c_e + V_X^i \frac{f_i}{c_i} = 0,
$$
(13)

where $i = 1, 2, i \neq j$. Solving the first-order conditions for enforcement effort yields:

$$
e_i = \frac{1}{f_i} \left(w_i + V_X^i - \frac{c_e c_i}{f_i} \right), \quad i = 1, 2.
$$
(14)

Note that the HJB equation is linear in the state variable X (the resource stock) and that the first-order conditions are therefore independent of the resource stock. Consequently, the game is a linear-state differential game. Following Dockner et al. (2000) we seek solutions of the form $V^i(X) = v^i X + b^i$. Inserting this into the HJB equation for V_i and collecting terms result in a system of algebraic Riccati equations, which we solve for v^i, b^i, where $i = 1, 2$, to obtain the solution.

Theorem 1. *A Markov perfect Nash equilibrium for this game exists and the equilibrium is given by*

$$
e_1^* = \frac{1}{f_1} \left(w_1 + \frac{w_1 \theta}{r - a} - \frac{c_e c_1}{f_1} \right)
$$
(15)

$$
e_2^* = \frac{1}{f_2} \left(w_2 + \frac{w_2 \theta}{r - a} - \frac{c_e c_2}{f_2} \right)
$$
(16)

Proof. The proof follows by solving the algebraic Riccati equations. Inserting the equilibrium strategies (equations 15 and 16) back into the HJB equation (12) yields:

$$
\begin{aligned}
rv^i X + rw^i &= p\frac{p-e_if_i}{c_i} - \frac{c_i}{2}\left(\frac{p-e_if_i}{c_i}\right)^2 - w_i\left(\frac{p-e_if_i}{c_i} + \frac{p-e_j(X,t)f_j}{c_j} - \theta X\right) - c_ee_i \\
&+ v_i\left[aX - \frac{p-e_if_i}{c_i} - \frac{p-e_j(X,t)f_j}{c_j}\right],
\end{aligned}
\tag{17}
$$

where $e_i = \frac{1}{f_i}\left(w_i + v^i - \frac{c_ec_i}{f_i}\right)$, and $i,j = 1,2$, $i \neq j$. Collecting terms in powers of X results in

$$
rv^i X = w_i\theta X + v^i aX, \ i = 1,2.
\tag{18}
$$

By solving for $v_i = \frac{w_i\theta}{r-a}$ $(i = 1,2)$ and substituting for v_i into equations (15) and (16), we obtain the equilibrium levels of enforcement effort for the two countries:[4]

$$
e_i^* = \frac{1}{f_i}\left[w_i\left(1 + \frac{\theta}{r-a}\right) - \frac{c_ec_i}{f_i}\right], \ i = 1,2
\tag{19}
$$

The remaining terms that are independent of X equate to b^i. □

Note that the only difference in equilibrium enforcement efforts between joint management and the dynamic game is that under joint management (social optimum) the enforcement effort of a country depends on the weight both countries put on sustainability $(w_1 + w_2)$. In the competitive case, a country's enforcement effort only depends on the country's own preferences toward sustainability (w_i). Hence, equilibrium enforcement levels in the dynamic game are lower than what is socially optimal $(e^* \leq e^{**})$. This is easily seen by comparing optimal joint enforcement (equation 9) to equation (19).

To find the equilibrium production levels for the two countries, we evaluate the reaction function of the firms (equation 3) at the countries' equilibrium enforcement efforts (equation 19). This yields:

$$
q_i^* = \frac{1}{c_i}\left[p - w_i\left(1 + \frac{\theta}{r-a}\right) + \frac{c_ec_i}{f_i}\right], \ i = 1,2.
\tag{20}
$$

Finally, to find the equilibrium stock level, we use the state equation for the resource stock, which in steady state requires $X = \frac{1}{a}(q_1 + q_2)$. Substituting in for the countries'

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[4]Throughout the paper, superscript * denotes the dynamic game equilibrium.

optimal extraction levels yields the following equilibrium resource stock level:

$$X^* = \frac{1}{a}\left[p\left(\frac{1}{c_1} + \frac{1}{c_2}\right) - \left(\frac{w_1}{c_1} + \frac{w_2}{c_2}\right)\left(1 + \frac{\theta}{r-a}\right) + c_e\left(\frac{1}{f_1} + \frac{1}{f_2}\right)\right]. \qquad (21)$$

Let us now turn to marginal effects of changes in model parameters. We start out by considering the impact of a change in quota on the level of compliance. Recall that country i's quota is given by $\gamma_i \theta X$ from equation (1), while the equilibrium production level q_i^* is given by equation (20). Denote the level of non-compliance with $A_i = q_i - \gamma_i \theta X$. By substituting in for equilibrium levels of the resource stock and extraction variables and taking the derivative with respect to θ, we can determine the effect of a change of quota on the level of compliance.

$$\frac{\partial A_i}{\partial \theta} = \frac{dq_i^*}{d\theta} - \gamma_i \theta \frac{dX}{d\theta} - \gamma_i X^* \qquad (22)$$

The effect a change in the quota has on the level of non-compliance depends on the current size of the quota (θ) and resource stock, as well as on other model parameters. The lower the extraction costs c, the stronger the preferences for sustainability w and the larger country i's share of the quota γ_i, the more likely that a tightening of the quota policy increases country i's compliance level.

Table 1: Comparative statics: How changes in parameters affect equilibrium outcomes

Parameter	Joint management			Dynamic game		
	e_i^{**}	q_i^{**}	X_i^{**}	e_i^*	q_i^*	X_i^*
a	$+$	$-$	$-$	$+$	$-$	$-$
p	0	$+$	$+$	0	$+$	$+$
f_i	$+/-^a$	$-$	$-$	$+/-^b$	$-$	$-$
θ	$+$	$-$	$-$	$+$	$-$	$-$
c_e	$-$	$+$	$+$	$-$	$+$	$+$
w_i	$+$	$-$	$-$	$+$	$-$	$-$
w_j	$+$	$-$	$-$	0	0	$-$
c_i	$-$	$+/-^c$	$+/-^c$	$-$	$+/-^d$	$+/-^d$

[a]Positive if $\frac{2c_i c_e}{f_i} > (w_1 + w_2)\left(1 + \frac{\theta}{r-a}\right)$

[b]Positive if $\frac{2c_i c_e}{f_i} > w_i\left(1 + \frac{\theta}{r-a}\right)$

[c]Positive if $p < (w_1 + w_2)\left(1 + \frac{\theta}{r-a}\right)$

[d]Positive if $p < w_i\left(1 + \frac{\theta}{r-a}\right)$

Finally, let us summarize the marginal effects of changes in parameters on enforcement effort, extraction levels and resource stock in equilibrium. An overview is provided in table 1. First, note that we only consider effects on equilibrium values. Hence, the quota and resource stock always move in the same direction since the steady-state condition for the resource stock requires $q_1 + q_2 = aX$. Second, most marginal effects have the same signs in the dynamic game as in the social planner case (joint management). The exception is the effect on extraction and enforcement levels of a change in player j's preference to sustainability. In this case, player i's extraction and enforcement levels are unaffected in the dynamic game whereas under joint management they move in the same direction as if the player's own preference to sustainability had changed. Finally, the marginal effect of changes in parameters are typically opposite on enforcement effort than on extraction and stock levels. This is because the higher the enforcement effort, all else equal, the lower the extraction level.

With this in place, we turn to our analysis of the governments' free-riding in enforcement effort.

3.3 Free-riding

We are now in a position to compare the outcome of the dynamic enforcement game with the social planner outcome (joint enforcement). Key questions are whether enforcement effort can be efficient in the competitive case. To investigate this we characterize the countries' incentives to free-ride. If a country's enforcement effort is lower in the competitive case than under joint enforcement, that is, if $e_i^* < e_i^{**}$, then the country is free-riding. We start out by looking at the requirements for a country to choose not to free-ride in the competitive case.

Theorem 2. *If $w_j = 0$ then $e_i^{**} = e_i^*$ and country i does not free-ride.*

Proof. $e_i^{**} - e_i^* = 0$ implies that

$$\frac{1}{f_i}\left[(w_i + w_j)(1 + \frac{\theta}{r - a}) - \frac{c_e c_i}{f_i}\right] - \frac{1}{f_i}\left[w_i(1 + \frac{\theta}{r - a}) - \frac{c_e c_i}{f_i}\right] = 0 \tag{23}$$

This simplifies to

$$w_j(1 + \frac{\theta}{r - a}) = 0 \tag{24}$$

This implies either $w_j = 0$ or $\theta = a - r$. However, the latter is not possible because $r > a$ and $\theta \in (0, 1)$. $\qquad\square$

Consequently a country will not free-ride as long as the other country places zero value on sustainability ($w_j = 0$). If a country does not value sustainability, it will exert

an enforcement effort of $e_j = 0$ (cf. equation 19). Hence, a country that cares about sustainability will keep its own enforcement level high (i.e., no free-riding) if it believes that the other country will exert no enforcement effort.

The governments choose enforcement effort by maximizing their discounted welfare. However, the objective function depends on the sustainability preference of the other country (w_j). There are several ways of interpreting this. First, it can be interpreted as if preferences are "other-regarding." This is a rather unusual assumption in economics where we generally assume "self-regarding" preferences.[5] Another interpretation is that the sustainability weights of country j are country i's beliefs about country j's environmental preferences, not its actual preferences. This is a standard approach within Bayesian game theory. We return to this below.

No-free-riding equilibrium

We have established that the only condition under which country i will choose to exert its joint management level of enforcement effort is when the other country does not value sustainability at all ($w_j = 0$). Therefore, in the no-free-riding case, the Markov perfect equilibrium is given by

$$e_1^* = \frac{1}{f_1}\left(w_1 + \frac{w_1\theta}{r - a} - \frac{c_e c_1}{f_1}\right) \tag{25}$$
$$e_2^* = 0 \tag{26}$$

or vice versa. This result can be interpreted as follows. If a country's government chooses not to free-ride, it must believe that the government of the other country does not care about sustainability, and therefore exerts no enforcement effort.

This equilibrium can explain why countries may want to obtain a "bad" reputation internationally, for example before going into climate negotiations. If country j can convince country i that it puts absolutely no value on sustainability (or on the global environment), country i may exert a higher level of enforcement nationally (the no-free-riding level) and hence, emit less greenhouse gasses. Country j can then emit more without the global climate being negatively effected compared to the case when both countries choose to free-ride in enforcement.

An implication of the no-free-riding Markov perfect equilibrium is that a situation where both countries choose socially optimal levels of enforcement cannot be reached, unless both countries incorrectly believe that the other country does not value sustain-

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[5]The interested reader is referred to the welfare economics literature for more detail on this. See for example (Ng, 2004)

ability at all. We obtain this symmetry result because theorem 2 is based on the i-th player optimizing an objective function that depends on j's preferences w_j. Hence, for country 1 to not free-ride theorem 2 requires $w_1 > 0$ and $w_2 = 0$, while for player 2 to not free-ride it requires $w_2 > 0$ and $w_1 = 0$. If preferences were other-regarding, this would be a contradiction. However, if we interpret the weights as beliefs, there is no contradiction as it implies that both countries under-estimate the weight of the other country and thereby the other country's enforcement effort.

An additional point that might be raised about this equilibrium is that in the course of time when a country observes that the other country's behavior is contradicting its expectations, it should revise its strategy. However, a Markov perfect equilibrium assumes that each country forgets the past behavior of the other country. The apparent inconsistency in expectations regarding the environmental preferences of the other country is a natural consequence of the Markovian information structure that we employ. A more realistic approach would allow for non-Markovian strategies. However, the analysis of non-Markovian strategies is beyond the scope of the paper and is left for future work.

To conclude, we have seen that although it is possible to end up in the joint management equilibrium without coordination, it is unlikely that both countries year after year incorrectly believe that the other country does not care about sustainability and therefore that both do not enforce their national quotas at all. Hence, it is far more likely that we end up in an equilibrium where both countries free-ride. This case is considered next.

Free-riding equilibrium

If a country free-rides, it exerts an enforcement effort below its optimal level under joint management: $e_i^{**} < e_i^*$. In this case we have that

$$ w_j(1 + \frac{\theta}{r-a}) > 0, \tag{27} $$

which is always true for $w_j > 0$ since we know that the term in parentheses is always positive.

Let us measure the level of free-riding by the difference in a country's enforcement effort under competition compared to the joint management case. Thus, the level of free-riding can be expressed as $e_i^{**} - e_i^* = \frac{1}{f_i} \left[w_j(1 + \frac{\theta}{r-a}) \right]$, and can be used to examine the impact of different policy measures on free-riding. Notice first that the level of free-riding is increasing in the country's belief about the other country's preference for

sustainability. This is because the lower the preference for sustainability, the lower the enforcement effort of the country, all else equal. Second, the level of free-riding is decreasing in the country's fine level f_i. Third, the level of free-riding is increasing in the quota parameter θ. A tightening of the quota leads to reduced enforcement effort regardless of whether we consider competition or joint management ($\frac{\partial e^*}{\partial \theta} > 0$ and $\frac{\partial e^{**}}{\partial \theta} > 0$). However, enforcement effort is reduced more following a tightening of the quota under competition than social planning, and hence, the level of free-riding goes down.

The fine f_i is usually determined exogenously by the legislative arm of government. The quota θ is determined by international agreements. Thus, neither variable is under the control of the national resource agencies. Hence, a hitherto unforeseen consequence of legislative policy measures targeted at firms that directly exploit the resources is that such measures have a disciplinary effect also on the national regulatory agency. If fines on firms are lowered this would not just encourage increased illegal resource exploitation by firms but it would also encourage increased free-riding on the part of the government. A similar story can be told for a tightening of quotas, but here the independent bodies that can affect the outcome of the game is the international agreement.[6] Consequently, from a policy perspective both legislators and international agencies responsible for setting policy parameters, are potentially able to commit to policy measures that reduce incentives for national governments to free-ride. Hence, the prospects for international sharing agreements to be successful increases considerably if e.g. national punishment levels for illegal resource use were increased. This requires that these policy variables cannot be changed by the national regulatory agencies. Tough standards will force the governments to act closer to what is socially optimal (joint enforcement optimum). A soft policy stance, on the other hand, is likely to encourage free-riding at the government level.

3.3.1 Implications of free-riding for the steady-state stock level

No free-riding has implications for the steady-state level of the resource stock. If we compare the steady-state stock level under social planning with that under competition, then in general $X^{**} < X^*$. At first sight this appears to be somewhat curious. The explanation is relatively simple and has to do with free-riding. Under free-riding each regulatory agency exerts less enforcement effort and as a result extraction levels are higher. For these levels of extraction to be sustainable, a higher stock level is necessary.

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[6]In the case of a renewable resource, a tightening of quotas is only an effective instrument against free-riding for fast growing resources (a approaching r). For slow growing resources, a tightening of quotas will have little impact on free-riding unless both countries value the environment quite highly.

Consequently, with free-riding the steady-state stock level is higher when regulatory agencies behave strategically, than under social planning. The result is summarized by the following theorem.

Theorem 3. $X^{**} < X^*$ *if and only if both regulatory agencies free-ride.*

Proof. In a steady state under both social planning and regulatory competition we have $X^{**} = \frac{1}{a}[q_1^{**} + q_2^{**}]$ and $X^* = \frac{1}{a}[q_1^* + q_2^*]$. Taking the difference between these yields $\Delta X = X^{**} - X^* = \frac{1}{a}[q_1^{**} - q_1^* + q_2^{**} - q_2^*]$. Under no free-riding $e^{**} = e^*$, this implies that for each country $q^{**} = q^*$ and that $\Delta X = 0$. We next turn to the free-riding case and employ proof by contradiction. Under free-riding $e^{**} > e^*$, which implies $q^{**} < q^*$ for each country. Substituting in and using $q(e) = \frac{p-ef}{c}$ results in $(e^* - e^{**})\frac{f_1}{c_1} > (e^{**} - e^*)\frac{f_2}{c_2}$. The left hand side of this inequality is negative by assumption but since the right hand side is positive we have a contradiction. Consequently $X^* > X^{**}$. □

Note that this result depends on the model structure. We assumed a linear growth function for the resource stock. This implies that there is no limit to how large the sustainable resource stock can be. If instead a logistic growth function had been used, there would be limits both on the sustainable resource stock and consequently sustainable extraction levels. Another model assumption that contributes to the result is the assumption that extraction costs are independent of the size of the resource stock. This is a standard assumption in the case of pollution, and is commonly used to explain population growth in models of schooling fisheries, such as herring and anchovy.

4 Effects of quota change

We have assumed that the total quota is determined by an independent international agency. Hence, the countries do not have any impact on how the quota is set. We now investigate the implications of a tightening of the quota. Conservationists are typically in favor of tighter quotas (reducing θ). The main concern of the resource industry, however, is profit.

Although we maintain the assumption of how quotas are determined, analyzing the implications of quota change suggests what type of pressure the countries could put on the agency that determines quotas. In negotiations over the terms of international agreements, such as the one considered here, countries may disagree on whether a tight or a more lenient approach should be taken when setting the quota. We analyze this by focusing on industry profits.

Before we turn to this, notice that both under competition and joint management a tightening of the quota leads to decreased enforcement effort and increases in production levels and resource stock in steady state (cf. table 1). Hence, in terms of aggregate profit a tightening of the quota would lead to an improvement. However, a country's industry may still be worse off, as the benefits of increased production and stock levels are not distributed equally between the countries. Instead, this is determined by the strategic enforcement choices of the two countries as well as by their shares of the total quota.

We examine the instantaneous profit of the representative firm of each country in steady state. Two cases are considered. One in which the governments exert the Pareto efficient enforcement levels (no free-riding) and one in which they defect (free-riding).

The profit of the representative firm of country i can be expressed as follows

$$\pi_i^o = pq_i^o - \frac{c_i}{2}(q_i^o)^2 - e_i^o f_i \left(q_i^o - \gamma_i \theta X^o\right), \tag{28}$$

where superscript o denotes scenario (dynamic game $o = *$ and optimal enforcement $o = **$). Note that the country's share of the total quota γ_i has no impact on the equilibrium production level, but does impact the firm's profit in equilibrium. The higher the share of total quota, the lower the expected fines, all else equal.

We can evaluate the impact of changing the total quota on the steady-state profit of firms by differentiating profit with respect to θ. If this is positive then increasing θ has a positive impact on profit while reducing θ has a negative impact on profit. The partial derivative of (28) with respect to θ can be expressed as:

$$\frac{\partial \pi_i^o}{\partial \theta} = [p - c_i q_i^o - e_i^o f_i] \frac{\partial q_i^o}{\partial \theta} - \frac{\partial e_i^o}{\partial \theta} f_i \left(q_i^o - \gamma_i \theta X^o\right) + e_i^o f_i \gamma_i \left(X^o + \theta \frac{\partial X^o}{\partial \theta}\right) > 0. \tag{29}$$

Note that we express the partial derivative as an inequality, because we are interested in identifying the conditions under which a change in quota increases industry surplus in a country.

The partial derivatives in (29) depend on whether we consider the Pareto efficient case where there is no free-riding, or if we consider the case where both countries free-ride. We start out by considering the Pareto efficient case.

No free-riding

In the Pareto efficient equilibrium both firms chooses the optimal joint management levels of enforcement. In this case each firm's profit is given by (28), with $o = **$. To analyze the impact on firm profit from a change in the total quota as indicated by θ,

we evaluate each of the derivatives in (29):

$$\frac{\partial q_i^{**}}{\partial \theta} = -\frac{w_1 + w_2}{c_i(r - a)} \tag{30}$$

$$\frac{\partial e_i^{**}}{\partial \theta} = \frac{w_1 + w_2}{f_i(r - a)} \tag{31}$$

$$\frac{\partial X^{**}}{\partial \theta} = -\frac{w_1 + w_2}{a(r - a)} \left(\frac{1}{c_1} + \frac{1}{c_2} \right). \tag{32}$$

Hence, for $r > a$, we have that $\frac{\partial q_i^{**}}{\partial \theta} < 0$, $\frac{\partial e_i^{**}}{\partial \theta} > 0$ and $\frac{\partial X^{**}}{\partial \theta} < 0$. Substituting these into inequality (29) and rearranging, we obtain a bound on γ_i:

$$\gamma_i > -\frac{[p - c_i q_i^{**} - e_i^{**} f_i]\frac{\partial q_i^{**}}{\partial \theta} - \frac{\partial e_i^{**}}{\partial \theta} f_i q_i^{**}}{f_i \frac{\partial e_i^{**}}{\partial \theta} \theta X^{**} + e_i^{**} f_i X^{**} + e_i^{**} f_i \theta \frac{\partial X^{**}}{\partial \theta}}, \tag{33}$$

if $\frac{\partial \pi_i}{\partial \theta} > 0$.

Since we are considering the case in which country i does not free-ride, we can assume without loss of generality that $w_1 > 0$ and $w_2 = 0$. This is appropriate because in the equilibrium where none of the two countries free-ride, both countries falsely believe that the other country puts zero value on sustainability. Hence, from country 1's point of view, $w_1 > 0$ and $w_2 = 0$. We could just as well analyze this from country 2's point of view, but the result would nonetheless be the same. Evaluating the derivatives given these assumptions about the countries' preferences to sustainability yields:

$$\frac{\partial q_1^{**}}{\partial \theta} = -\frac{w_1}{c_i(r - a)} \tag{34}$$

$$\frac{\partial e_1^{**}}{\partial \theta} = \frac{w_1}{f_i(r - a)} \tag{35}$$

$$\frac{\partial X^{**}}{\partial \theta} = -\frac{w_1}{a(r - a)} \left(\frac{1}{c_1} + \frac{1}{c_2} \right). \tag{36}$$

Consequently we obtain a bound on γ_1, which after simplifying evaluates to:

$$\gamma_1 > \frac{\frac{w_1}{(r-a)} \frac{p - \left[w_1(1 + \frac{\theta}{r-a}) - \frac{c_e c_i}{f_1} \right]}{c_i}}{\frac{w_1}{(r-a)} \theta X^{**} + e_1^{**} f_1 X^{**} - e_1^{**} f_1 \theta \frac{w_1}{a(r-a)} \left(\frac{1}{c_1} + \frac{1}{c_2} \right)}. \tag{37}$$

The quota share of the other country plays no role in determining whether or not the country in question benefits from an increase in the quota. This can be seen by

simplifying equation (29), which results in

$$X^{**} - \theta \frac{w_1 + w_2}{a(r-a)} \left(\frac{1}{c_1} + \frac{1}{c_2} \right) > 0. \tag{38}$$

The latter equation implies either a bound on the steady-state stock of the resource, or alternatively, a bound on the quota in order for firms in the second country to profit from quota increases.

Recall that as θ increases, a greater proportion of the resource stock can be exploited, while as θ decreases the exploitable portion of the resource becomes smaller (quota is tightened). Consequently, the impact of a tightening of the quota only has a detrimental impact on industry profit in steady state if the industry's share of the total quota is high, as defined by the above inequality (38).

For a country that does not free-ride, the consequences of changes to the quota policy depend on the sharing of the resource. Countries with large shares of the quota have more to lose from a quota tightening than other countries. This is reflected in equation (37), since the higher the value of γ_1 the more likely that industry profits are negatively affected by a tightening of the quota.

Notice that the non-free-riding country does not believe that the resource share plays a role in the profit response of the other country to changes in quota. This is because a country that does not free-ride, wrongfully believes that the other country does not care about sustainability (cf. theorem 2), and hence, does not enforce its national quota. If national quotas are not enforced, the resource industry will exploit the resource as if there was no quota. Therefore, theorem 2 implies that the non-free-riding country believes that the national quota of the other country will have no impact on that country's resource industry.

Free-riding

We now proceed with the same analysis for the strategic case, which is the relevant case in the event of free-riding. The relevant profit function in this case is given by equation (28), with $o = *$. We employ the same envelope condition as before but now the partial derivatives will differ.

By evaluating each of the derivatives we see that

$$\frac{\partial q_i^*}{\partial \theta} = -\frac{w_i}{f_i c_i (r-a)} \tag{39}$$

$$\frac{\partial e_i^*}{\partial \theta} = \frac{w_i}{f_i (r-a)} \tag{40}$$

$$\frac{\partial X^*}{\partial \theta} = -\frac{1}{a(r-a)} \left(\frac{w_1}{f_1} + \frac{w_2}{f_2} \right) \left(\frac{1}{c_1} + \frac{1}{c_2} \right). \tag{41}$$

If $r > a$, we have that $\frac{\partial q_i^*}{\partial \theta} < 0$, $\frac{\partial e_i^*}{\partial \theta} > 0$ and $\frac{\partial X^*}{\partial \theta} < 0$. Substituting these into the inequality (29) and rearranging we obtain a bound on γ_i:

$$\gamma_i > \frac{[p - c_i q_i^* - e_i^* f_i] \frac{w_i}{f_i c_i (r-a)} + f_i q_i^* \frac{w_i}{f_i (r-a)}}{\frac{w_i}{(r-a)} \theta X^* + e_i^* f_i X^* - e_i^* f_i \theta \left(\frac{1}{a(r-a)} (\frac{w_1}{f_1} + \frac{w_2}{f_2})(\frac{1}{c_1} + \frac{1}{c_2}) \right)}, \tag{42}$$

if $\frac{\partial \pi_i}{\partial \theta} > 0$. Consequently, the country with a relatively large share of the total quota will be hurt by a tightening of the quota. This is the same as we found in the Pareto efficient case without free-riding. However, in the competitive case, countries will believe that the other country is also affected by the change in quota (i.e., cares about sustainability).

To summarize, we have found that whereas the overall welfare in steady state is improved following a tightening of the total quota, a country who is entitled to a large share of the quota may in fact be worse off. This result is independent of whether countries exert suboptimal levels of enforcement (free-riding) or if countries exert enforcement efficiently. However, the minimum share of the total quota a country must have to be negatively affected by a quota tightening depends on whether there is free-riding in enforcement or not. In our analysis we focused on the effect on firms' profits. This is an important part of the countries' welfare, but does not take into account sustainability concerns.

5   Conclusion

In this paper we have examined competition in quota enforcement between two nations when the industry in each nation is characterized by competitive behavior. The results demonstrate under what conditions national agencies are likely to free-ride vis-a-vis an international cooperative agreement and what impact the tightening of international quotas may have on the welfare of each country's industry. We find that countries with

relatively large shares of international quotas will suffer from a tightening of quotas, while smaller countries may in fact benefit.

Our competitive equilibrium shows why countries may want to obtain a bad reputation in the international management of CPRs. If a country can convince other countries that it puts no value on sustainability, other countries may exert higher levels of enforcement to compensate. Hence, obtaining "bad boy" status in settings such as the global move towards curbing greenhouse gas emissions can pay off for a country, regardless of what its true preferences are regarding sustainability.

Another result we obtain is that free-riding at the country level is reduced if the total quota is reduced or if the national punishment level for quota violations increases. This offers valuable policy advice. Since both policy instruments (fine level and total quota) are generally controlled by others than the national resource regulators, these instruments could potentially be used to increase the efficiency of international sharing agreements. The reason is that they give each country's resource regulator incentives to increase the enforcement of national industries. Hence, if all countries sharing a resource commit to increased punishment levels, the level of enforcement in each country and the level of aggregate welfare would increase.

Let us now return to the shared resource cases mentioned in the introduction. Consider first GHG emissions governed by international treaties such as the Kyoto Protocol, and regional emissions agreements aimed at limiting SO2 emissions (and acid rain). Our results imply that care should be taken when setting emission limits in such agreements. The tighter the emission targets, the lower the national enforcement levels and the lower the expected punishment for firms that violate emission regulations. However, we find that also equilibrium emission levels fall with a tightening of the quota. Hence, despite more lenient enforcement, the overall effect is an improvement in terms of emissions. Furthermore, to increase the efficiency of international emissions agreements by reducing free-riding, efforts should be taken to make treaty countries change legislation to increase national punishment levels for violations of emission standards and regulations. The judicial system is typically relatively independent of other government bodies, and hence, the players in the international enforcement game take national punishment levels as given. As a consequence, increased punishment levels results in better national enforcement. This, in turn, increases the efficiency of the international environmental agreement by reducing total emissions.

Consider next the Norway-Russian cod fishery in the Northeast Arctic. According to the quota sharing agreement, the total cod quota is shared approximately 50-50 between the two countries. Third-party nations are allowed to take part in the fishery, which comes out of the two main countries' quota shares. Both the Norwegian and

Russian quotas are substantial. A tightening of the total quota is therefore likely to be detrimental for both countries' industries. In spite of this, there has in recent years been much controversy over how the total quota is determined. Russia has argued that the quota recommendations from the International Council for the Exploration of the Sea (ICES) have been too restrictive. Norway, on the other side, has argued in favor of following ICES advice. The fishery has been characterized by large unreported catches. Based on the results presented above, an increase in the total quota would strengthen the countries' incentives to toughen enforcement in order to limit illegal catches in the fishery. However, an increase in the total quota causes catch levels to increase and the effect on compliance depends on current stock and quota levels as well as the model parameters. Empirical analysis is therefore required to conclude whether an increase in the total quota would reduce the level of illegal landings.

There are many ways to extend this work. The results go some way in explaining the respective positions of nations in international negotiations on determination of the nations' shares of the resource. However, we have assumed that the sharing of the resource is given and thereby disregarded any strategic interaction at that stage. This represents a possibility for future research. In addition, the analysis could be extended to consider non-Markovian strategies such as trigger strategies. This would likely affect the no-free-riding equilibrium, which depends heavily on the assumption of "no memory" of past behavior inherent in the Markov perfect equilibrium concept.

Furthermore, the welfare analysis of the effect of changing the quota is done at each point in time not over the whole time path of stock exploitation. A similar analysis could be conducted for the whole time path by examining intertemporal value functions rather than instantaneous industry profits. A further extension would involve analyzing different industry structures within each nation. This increases the complexity of the analysis considerably but may suggest some different conclusions in terms of steady-state results. If one nations industry is more concentrated, this would introduce interesting asymmetries into the behavior of each nation. We leave these more complex scenarios for future work.

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APPENDIX

A Derivation of steady-state

The second first order condition (7) is a linear non-homogeneous differential equation, which can be solved for $\lambda(t)$ using the integrating factor $e^{(r-a)t}$ to obtain:

$$\lambda(t) = e^{(r-a)t} \int e^{-(r-a)t}(-\theta(w_1 + w_2))dt \tag{43}$$

Integrating equation (43) by parts we obtain

$$\lambda(t) = e^{(r-a)t}[-(r-a)^{-1}e^{-(r-a)t}(-\theta(w_1 + w_2)] = \frac{\theta(w_1 + w_2)}{r-a}, \tag{44}$$

which is seen to be constant and independent of time. Substituting $\lambda(t)$ from (44) into equation (8) gives us the optimal enforcement level:

$$e_i^{**} = \frac{1}{f_i}\left[(w_1 + w_2)[1 + \frac{\theta}{r-a}] - \frac{c_e c_i}{f_i}\right]. \tag{45}$$

The optimal enforcement level e_i^{**} can then be used to calculate the optimal production for each industry from equation (3):

$$q^{**}(e) = \frac{p - \left[(w_1 + w_2)\left(1 + \frac{\theta}{r-a}\right) - \frac{c_e c_i}{f_i}\right]}{c_i}. \tag{46}$$

Since the state equation is linear we can obtain an explicit analytical solution for the optimal resource stock level. Writing the state equation in the following form:

$$\dot{x} - ax = g(t), \tag{47}$$

where $g(t) = -q_1^{**}(e) - q_2^{**}(e)$, the differential equation may be solved using the integrating factor e^{-at}:

$$x(t) = \frac{\int e^{-at}g(t)dt}{e^{-at}} = e^{at}\int e^{-at}g(t)dt \tag{48}$$

Integrating equation (48) by parts we obtain:

$$x(t) = e^{at}[-a^{-1}e^{-at}g(t)] - e^{at}\int(-a^{-1})e^{-at}g'(t)dt \tag{49}$$

$$x(t) = e^{at}[-a^{-1}e^{-at}(-q_1^{**}(e) - q_2^{**}(e))]$$
$$-e^{at}\int(a^{-1})e^{-at}\left(\frac{\partial q_1^{**}(e)}{\partial e_1}\dot{e}_1 + \frac{\partial q_2^{**}(e)}{\partial e_2}\dot{e}_2\right)dt \tag{50}$$

By taking the limit $t \to \infty$, the integral vanishes and we find the steady-state stock:

$$X^{**} = \frac{1}{a}\left[\frac{p - e_1^{**}f_1}{c_1} + \frac{p - e_2^{**}f_2}{c_2}\right]. \tag{51}$$

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